Stephen J. Lycett
Parth R. Chauhan
Editors

New Perspectives on Old Stones

Analytical Approaches to Paleolithic Technologies

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Chapter 1
Analytical Approaches to Palaeolithic Technologies: An Introduction

Stephen J. Lycett and Parth R. Chauhan

Abstract We believe that it is instructive and timely to revisit themes that David L. Clarke (1968) raised in *Analytical Archaeology*. Here, we examine the extent to which they are being pursued by the contributors of this volume in the context of Palaeolithic studies. In highlighting certain "Clarkeian" trends, we discuss four themes: (1) hypothesis testing and formal analysis, (2) quantification and inferential statistical analysis, (3) models, (4) cultural transmission and lineages of artefactual traditions and (5) morphometrics.

Rationale Behind This Volume

As often noted, artefacts made from stone constitute the primary source of evidence regarding the behaviours and activities of fossil hominins and humans for the majority of prehistory. This volume grew out of a symposium (*Analytical Approaches to Palaeolithic Technologies*) held at the 2008 Society for American Archaeology meetings in Vancouver, Canada. The session had two primary aims. The first of these was to bring together as many people as possible who had demonstrated an interest in pursuing quantitative, hypothesis-driven, analytical approaches to the study of stone tools, particularly via novel techniques. The second aim was to draw attention to the fact that 2008 was the 40th anniversary year of David Clarke's landmark volume *Analytical Archaeology*. We particularly felt that many of the principles, approaches and techniques highlighted at the symposium owed something of their origin to issues raised and discussed by Clarke, hence the title of our session. It may give readers of this volume greater insight to our motivations if they consider our original SAA abstract:

> In the fortieth anniversary year of David Clarke's instrumental volume *Analytical Archaeology*, the central theme of this session is the *analysis of Palaeolithic technologies*,

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> using a variety of quantitative and formal analytical procedures. The session will aim to incorporate a broad chronological and geographical range of Palaeolithic material from the Lower to Upper Palaeolithic. However, in all cases, participants will be encouraged to emphasise *analysis* of lithic material and novel approaches used therein, rather than its mere description or archaeological "philately".

Given that a majority of participants from the symposium were able to contribute to the current volume, we hope that many of the original aims and sentiment of the session have successfully been carried over into the pages that follow. We are particularly pleased that the chapters cover a variety of different approaches (albeit with some dominant themes, as discussed below), and that material from both the Old and New Worlds is incorporated, which has ensured retention of a broad chronological coverage.

Rather than give a detailed "overview" of each chapter, what we hope to do in this introduction is highlight several apparent research themes that Clarke (1968) discussed in *Analytical Archaeology* (and elsewhere). We hasten to add that this should not be taken to mean that the current volume is intentionally a "tribute" volume to Clarke, much less a deliberate festschrift. It is also not even to be taken to mean that all of the contributors necessarily subscribe to all aspects of Clarke's views, nor even necessarily consider him a direct influence. Rather, given that four decades have now passed since the publication of his landmark volume, we believe that from an editorial viewpoint it is instructive and timely to revisit themes that Clarke raised, and to examine the extent to which they are being pursued by the contributors of this volume. It is, of course, also important to note at the outset that Clarke's book was not exclusively orientated toward the study of stones tools, but was aimed at instigating a much broader agenda for prehistory and archaeology in general. It must also be remembered that Clarke's own views were part of a wider set of changes going on within (the "New") archaeology at the time, and concurrent with the writings of some equally influential figures, perhaps most notably, Lewis Binford (for historical overviews see e.g. Trigger 1989; Shennan 1989, 2004; O'Brien et al. 2005). However, as we hope to demonstrate in the following sections, several particular themes that Clarke advocated as providing avenues for a rigorous interrogation of prehistoric evidence, appear to be alive and well in some current research being pursued in the field of lithic studies. Indeed as we aim to show, such themes, if anything, appear to have seen something of a resurgence within the last few years.

Exploring the Legacy of David Clarke in the Contemporary Analysis of Palaeolithic Data

In highlighting certain "Clarkeian" trends, we note five particular themes, all of which are elaborated upon below in relation to the contributions in this volume as explicit examples: (1) hypothesis testing and formal analysis, (2) quantification and inferential statistical analysis, (3) models, (4) cultural transmission and lineages of artefactual traditions and (5) morphometrics.

Hypothesis Testing and Formal Analysis

> *Hypotheses are developed to relate observed properties to one another by means of a structural concept. In this way an hypothesis, or an hypothetical model, is constructed for the sake of predicting certain correlated regularities*
>
> D.L. Clarke (1968: 643)

In a letter to a colleague discussing the practice of scientific endeavour, Charles Darwin once remarked: "How odd it is that anyone should not see that all observation must be for or against some view if it is to be of any service!".[1] He also remarked in the same letter that in the absence of such a standpoint, one "might as well go into a gravel-pit and count the pebbles and describe the colours". Sadly, in our own field, we have probably all seen examples of lithic studies that appear little more than pebble counting.

As much as any particular "technique", the word *analytical* in the title of Clarke's (1968) treatise refers to the more general philosophical principle of using formal empirical observations in the building and testing of hypotheses. "Formal" in this instance refers to the use of quantitative data (be it categorical, ordinal or metric), to assess in a detailed manner the relationship (or otherwise) between a set of empirical phenomena and a particular model or hypothesis derived from theory or observation, the assumptions and predictions of which are made explicit. Such an approach can be contrasted with those of description and narrative.

As discussed by Hill (1972) in Clarke's (1972) *Models in Archaeology*, in this sense the word "analysis" takes on a quite different and particular meaning from the way it is all too commonly applied (Hill 1972: 86), structuring everything from question posing, hypotheses, predictions (i.e. the test implications of hypotheses) to data collection, to result "interpretation". Wryly, Hill (1972: 88) suggests that there is an advantage to structuring research design according to a sequence of "problem"→ "hypothesis"→"data", rather than the inverse of "data"→"hypothesis"→ "problem"! We hasten to point out that we ourselves do not see strict hypothesis testing as the *only* means to viable analysis. Indeed, the authors in this volume differ in the extent to which their analyses are framed in a strict hypothesis testing framework: all, however, assess in a formal manner relationships between a set of empirical phenomena and a particular model or hypothesis derived from theory. Indeed, even Hill (1972: 62) pointed out that a strict distinction between inductive and deductive reasoning is somewhat false because both will be used at various points in an ongoing research programme. Rather, what we would suggest is that formal hypothesis testing should become more regularly used once again in Palaeolithic enquiry. It appears to have been out of vogue for a majority of workers, meaning that an important tactic in the lithic analyst's tool kit has been under-utilized, if not, under-taught. Several contributors in this volume, however, delineate hypotheses and explicitly test their predictions.

[1] Quoted in F. Darwin, The Life and Letters of Charles Darwin, vol. II (John Murray, London, 1887), p. 121.

Some of the clearest examples can be seen in the chapters by Buchanan and Collard, Clarkson, and Monnier and McNulty (see also, Costa).

Buchanan and Collard test two hypotheses concerning traditionally recognised "shape-types" in Palaeoindian projectile points. The first hypothesis concerns the notion that blade shape effectively discriminates between projectile points from different traditionally held types. Hence, the prediction underlying this hypothesis is that shape information classifies points to "type" with high degrees of efficacy. They tested this prediction with a multivariate classification procedure [discriminant function analysis (DFA)]. Results of this first analysis were mixed: blade shape was able to provide a reliable basis for discrimination in some cases, less so in others. In their second analysis, Buchanan and Collard tested a hypothesis originally put forward by Flenniken and Raymond (1986), which proposed that resharpening of projectile points is likely to reduce the ability for discrimination between traditionally held Palaeoindian "types" due to sharpening-induced convergence in shape. Hence, the prediction in this analysis is that smaller points should have greater misclassification rates than larger points. This prediction was not supported in Buchanan and Collard's results, thus undermining the basic premise upon which the resharpening/convergence hypothesis is based.

Raw material has also long been thought of as a major, if not dominant, influence on the form of stone artefacts (e.g. Goodman 1944) such that it might outweigh the influence of cultural tradition. In his chapter, Clarkson also uses the classification technique of DFA to test the hypothesis that raw material is of greater influence than factors such as cultural tradition in discriminating between cores from the Howiesons Poort MSA of southern Africa. Using the DFA multivariate statistical procedure, Clarkson tests the extent to which different cores are correctly assigned both to raw material type and to geographic region. He finds that cores are correctly classified by raw material type in only 46% of cases, while cores are correctly classified to region in 72.8% of cases. Hence, Clarkson correctly cautions that both raw material and regional traditions appear to be influencing core shape, but also notes that "raw material differences would appear to be subservient to other causes of variation in creating differences between regions". Clarkson's analysis shows that even within a hypothesis testing framework, the relative influence of alternative – but not necessarily mutually exclusive – influences on stone tool form can be evaluated objectively and formally.

Monnier and McNulty test a hypothesis concerning the thorny topic of "behavioural modernity", especially as it relates to cognitive evolution. As these authors note, it has for some time been contended that standardization of lithic artefacts is an indicator of behavioural modernity. Monnier and McNulty test the extreme prediction of this "standardization hypothesis"; that is, that artefacts made by anatomically modern humans (AMHs) are always more standardised than those of non-moderns (i.e. Neanderthals). Using geometric morphometric techniques they show that Neolithic artefacts are not always more standardised than those of Neanderthals. As the authors note, this rejection of the strict prediction of the "standardization hypothesis" does not rule out a "softer" version of the hypothesis suggesting that AMHs had a greater *capacity* to standardize. However, it does show that standardization itself is a variable that is independent of, and not necessarily

directly reflective of, cognition or "modernity". Rather, alternative explanations for standardization in artefacts (e.g. function, raw material, tradition) should be explored as causes of standardization, at least on an equal basis. Monnier and McNulty's analysis is illustrative of one of the epistemological strengths of the hypothesis testing approach in terms of transparency regarding what a set of data does – and equally important – does not tell us about a specific issue, and in so doing allows robust and clear assessment of the value of results in moving both knowledge and debate forward.

Model building and the assessment of goodness-of-fit between empirical data and a model's parameters can be seen as a specific form of hypothesis testing (Clarke 1972), which is also used by several contributors here (e.g. Brantingham, Braun, Grove, Lycett, Shott). However, given the particularly prominent position that the use of models took in Clarke's overall philosophy, we discuss this in a separate section below.

The use of experimental archaeology can also be seen as a specific form of hypothesis testing (Clarke 1972: 54), which has great applicability in the case of functional items such as stone tools (Hiscock and Clarkson 2005; Shott et al. 2000; Shea et al. 2001; Patten 2005). We detect something of a recent reinvigoration and diversification in the use of quantitative experimental procedures for the analysis of lithic technologies. Recent examples of this include Machin et al.'s (2007) quantification of biface form and their assessment of variation in specific morphological parameters and efficiency in terms of butchery speed. Other examples include Sisk and Shea's (2009) study of Levallois point performance during trials as projectile points, and also Eren et al.'s (2008) assessment of the productivity in blade cores versus discoid cores. Toth et al.'s (2006) quantitative comparative analysis of experimental flakes produced by humans and Kanzi the bonobo (*Pan paniscus*) chimpanzee – directly alongside the earliest Oldowan examples from Gona, Ethiopia – provides a further example. Equally exciting, is the experimental work of Stout and colleagues which uses brain imaging technology to study brain function during the replication of prehistoric stone tools (Stout 2006; Stout et al. 2000, 2006; Stout and Chaminade 2007). In this volume, Clarkson uses experimentally knapped cores in order to assess the utility of a novel method for quantitatively describing core morphology, prior to moving on to an archaeological case study. Likewise, Braun and colleagues test their 3D method for calculating flake platform surface area (and subsequent determination of flake size) against a series of experimental pieces made on the same raw material as Oldowan artefacts from the Okote Member of the Koobi Fora Formation, northern Kenya.

Quantification and Inferential Statistical Analysis

> *Counting and measuring reduce vagueness, increase specificity, upgrade standards of arguments, allow error estimates, numerical manipulation and explicit* testing *of hypotheses*
>
> D.L. Clarke (1972: 55, emphasis in original)

In the above quoted sentence, David Clarke succinctly summarizes the major merits of quantitative, and particularly statistical, approaches over alternative forms of argumentation: repeatability, precision, robusticity and testability. Statistics are, of course, not infallible – they are statements of probability, not of fact. However, even this fallibility is a strength since the recognition, and more importantly, correction of any such error is facilitated – via transparency of operation – and in turn assists our ability to improve upon and extend previous studies via further empirical work. In so doing, research results have a greater potential to become progressively cumulative, thus helping to avoid the downward spiral of knowledge that results from argumentation of the "if, but, maybe" variety (see Clarke 1972: 43 for an interesting discussion on the growth of archaeological knowledge from this perspective).

In this volume, Grove highlights the wry observation of Hammond (1979: 7) who noted that due to David Clarke's advocacy of quantification in archaeological analysis his books "were usually ignored by the most traditional-minded of British archaeologists". Fortunately, however, archaeology has seen an increased use of quantitative and statistical methods over recent decades, which is of course at least partly driven by the now commonplace presence of powerful desktop computers and increased availability of more user-friendly software. Indeed, arguably, lithic studies have seen a greater use of quantitative data than even some other areas of archaeology. This is because lithic artefacts lend themselves to being counted and measured, and are often the only piece of archaeological evidence actually recovered from a prehistoric "site". It is unsurprising, therefore, that even introductory textbooks on lithic studies involve discussions on using quantitative data (see e.g. Andrefsky 1998; Kooyman 2000).

Despite this apparent widespread use of quantitative data in our field, however, it might still be doubted whether the use of statistical methods – particularly inferential statistics[2] – are a prominent mode of practice in lithic studies. Rather, it might be argued that the most frequent use of quantitative data in lithic studies consists of little more than a table of range values for a set of given variables (i.e. maximum and minimum values), their mean, and if we are lucky, a standard deviation. Darwin might have referred to this practice as *fancy* pebble counting. Such a practice is usually followed by an "interpretation" or theory of what such data may or may not mean. In other words, only a subset of lithic studies take the extra step of utilising this hard-won data more formally, within an explicitly hypothesis testing or model-fitting framework, via the use of inferential statistics.

Reasons for this are potentially mixed. It is understandable, for instance, that lithic studies, as in archaeology in general, draws people who are more thrilled by

[2] *Inferential statistics* is the branch of statistical analysis that allows determination of statistical significance, whereby differences or patterns in datasets can deemed meaningful according to quantifiable probability. Hence, inferences may be drawn about a set of data within the bounds of statistical confidence limits. Inferential statistics are in this sense distinguishable from *descriptive statistics*, which merely describe data in different ways (i.e. counts, range values, averages, standard deviations, etc.) (see Shennan 1997 for further discussion).

the thought of holding an artefact made millennia ago than they are by the thought of sitting down with a manual describing, for example, Discriminant Function Analysis. This, at least for some students, may be compounded by a lack of formal training. Indeed, despite the commonplace presence of computers, it might prove an informative exercise to determine whether the average archaeology undergraduate spends as much time as an average biology undergraduate being trained in statistical methods, despite the importance of quantitative data in both fields. Such a situation leads to an impasse more problematic than simply a failure to utilize an important set of research tools or even simply a passive tendency to ignore results from studies that use statistical approaches: it leads to ignorance, and ignorance breeds active resentment or what Shennan (1997: 1) has referred to as "rejection on the basis of uninformed prejudice". Correction of such prejudice can be achieved by enthusiastic instructors, but scholars interested in pursuing these techniques may also have to take matters into their own hands and make the efforts required to learn these techniques (and their underlying principles) for themselves. Fortunately, given the increased number of user-friendly statistical manuals and software packages appearing in recent years, this is now arguably a more achievable task than ever before.

Presumably, David Clarke would have been pleased to observe that all the contributors to the current volume use statistical methods of one sort or another. He would presumably also have been pleased to see the breadth of statistical

Table 1.1 Main statistical procedures used in this volume

Statistical procedure	Chapter(s)	Category of technique	Further reading
Boxplots/Box-and-whisker plots	Brantingham, Braun et al., Clarkson	Descriptive	Shennan (1997)
Kruskal Wallis	Monnier and McNulty	Inferential	Quinn and Keough (2002)
Mann Whitney U test	Chauhan	Inferential	Shennan (1997)
MANOVA (Multivariate Analysis of Variance)	Buchanan and Collard, Costa	Inferential	Hair et al. (1998) and Quinn and Keough (2002)
Regression	Braun et al., Lycett	Inferential	Shennan (1997) and Quinn and Keough (2002)
Cluster analysis	Chauhan	Multivariate	Shennan (1997) and Hair et al. (1998)
PCA (Principal Components Analysis)	Costa, Ioviţă	Multivariate	Shennan (1997) and Hair et al. (1998)
CVA (Canonical Variates Analysis)	Costa	Multivariate	Hair et al. (1998)
DFA (Discriminant Function Analysis)	Buchanan and Collard, Clarkson	Multivariate	Hair et al. (1998)
Cladistics	Lycett	Multivariate	O'Brien and Lyman (2003) and Kitching et al. (1998)

Note that specialist model-fitting and morphometric procedures used by some contributors are not listed

techniques deployed. Table 1.1 describes the main statistical procedures used by the chapter authors at various stages of their analyses. The methods listed include combinations of descriptive procedures (e.g. box-and-whisker plots) multivariate procedures (e.g. DFA, PCA), as well as inferential statistics (e.g. MANOVA, regression). As will be noted, some chapters contain nested combinations of several statistical procedures. In the interests of assisting the inquisitive reader who may wish to learn something more about these techniques (see point mentioned in the previous paragraph), the table also provides references to sources that describe the techniques in more detail. It should, of course, be remembered that even Table 1.1 comprises only a small subset of the procedures that may be of utility to lithic specialists, and the literature listed will also give fuller accounts of some of these additional methods. It should also be noted that the statistical methods listed in Table 1.1 are in addition to some of the more specialised procedures associated with the quantitative model-fitting techniques used by some contributors (e.g. Brantingham, Braun et al., Grove, Shott) and the specialised morphometric techniques used in some chapters (e.g. Braun et al., Clarkson, Costa, Lycett, Iovita, Monnier and McNulty), although useful references may be found in the relevant chapters pertinent to these techniques, in addition to the descriptions provided by the authors themselves.

Models

As noted earlier, the application of formal models might be seen as a particular category of hypothesis testing. Models, of course, occupied a prominent position in the overall philosophy of Clarke (1968, 1972) who recognised their pivotal role in structuring and sharpening a set of theoretical expectations to the point that archaeological data could be employed in a more robust role than one of polemical narrative. As Clarke (1972: 1) put it "[m]odels are pieces of machinery that relate observations to theoretical ideas". There are, however, several distinct categories of model ("machine") that are of use to archaeologists, including lithic analysts (Clarke 1972; Gibbon 1984).

Clarke (1972: 10–42) noted that the most useful forms of model for the archaeologist can be classed under the general term of "Operational Models". Such models come in a variety of guises but all act as a theoretical apparatus for deriving a set of predicted parameters based on explicit logic, which can then be measured for goodness-of-fit against empirical data. Their emphasis is, therefore, on predicting the empirical outcomes of a specified operational process, whereby in instances of high goodness-of-fit, that process can then reasonably be assumed to have been in operation thus potentially explaining *why* parameters in the archaeological record take the form they do. Under this general definition of "Operational Model", three sub-categories of model can be discerned: mathematical models, analogue models

and null models. It should be noted that these three categories of model are not necessarily mutually exclusive and sometimes overlap in certain properties.

Mathematical models: This form of model is based purely on logic (i.e. no empirical information is necessary *a priori* for their construction). They consist of "functions" written in calculus where numbers or symbols represent defined properties [which is why they are sometimes referred to as *symbolic models* or *iconic models* (e.g. Clarke 1972; Gibbon 1984)]. They express the relationship between specific properties in precise mathematical terms. Sometimes such models also form the basis of simulation, which are increasingly popular in archaeology with the greater ease of access to powerful computers (e.g. Shennan 2001; Henrich 2004; Lipo et al. 1997; Brantingham, this volume).

Gibbon (1984: 112) provides a somewhat crude but illustrative description of how a mathematical model potentially operates in archaeological settings, which can be modified to a hypothetical lithic example. In Fig. 1.1a, X represents weight of a stone hammer used during flake removal from a core, and Y represents the average length of flake scars produced during this operation. Under such circumstances, X is the independent variable, Y is the dependent variable, and b is the function (linear coefficient) that allows calculation of Y when given a value for X. The model can thus be expressed as $Y = bX$. In Fig. 1.1b, the model is extended by adding an additional independent variable (Z) which represents the use of a second hammer stone of a different weight than given for X. The new multivariate formula for the dependent variable Y thus becomes $Y = b_1X + b_2Z$.

Examples of the use of mathematical models of this nature in the current volume can be seen in the chapter by Brantingham on core reduction. In his contribution, Brantingham uses three models representing independent decisions during the reduction of cores, which take their names from their mathematical properties: These are the Bernoulli model, the Markov model and the Price model. Brantingham tests the goodness-of-fit between the parameters of each model against an archaeological data set for which the assumptions of the particular model might *a priori* reasonably be expected to hold true. The Bernoulli model is evaluated with a series

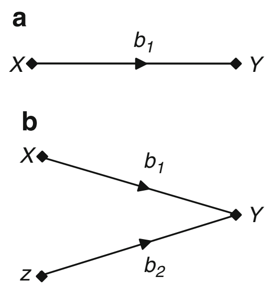

Fig. 1.1 (**a**, **b**) Hypothetical example of a simple mathematical model (Modified after Gibbon 1984: 112)

of Oldowan cores from Olduvai Gorge (Tanzania), and the Markov and Price models are compared against an assemblage of Upper Palaeolithic Levallois blade cores from Shuidonggou (northwest China). In determining where the models' parameters fit and do not fit the empirical data, Brantingham is able to demonstrate tactical decisions on the part of the knapper. For instance, a key prediction of the Bernoulli model is that poor quality raw material will be more intensively reduced. However, in the case of the Oldowan cores from Olduvai Gorge, Brantingham demonstrates that a directly contradictory pattern is present whereby higher quality raw materials are more intensively reduced. Such analyses are representative of some of the fundamental protocol of utilizing mathematical models (and indeed models in general) in terms of making a series of simplifying – but precise and explicit – assumptions, such that parameter values taken from empirical data can be compared for goodness-of-fit against those precisely laid out assumptions.

Further examples of mathematical modelling can be seen in the chapter by Grove, who provides functions for hypothesised hunter-gatherer movements between sites (e.g. the Lévy Walk). This "random walk" model has been shown to adequately characterise the movements of some non-human animals, and Brown et al. (2007) have suggested that it accurately depicts foraging patterns of the Dobe area !Kung of Botswana. Here Grove re-applies the model to data from the !Kung and compares it alongside an additional (lognormal) model. Grove finds that the Lévy Walk model effectively characterizes some aspects of movement in these hunter-gatherers, but not all. In particular, the very large numbers of small distances predicted by the Lévy model do not occur. Indeed, he finds that the lognormal model provides a better fit to the data in this regard. He uses this observation to further hypothesise on the nature of movement strategies in the !Kung and hunter-gathers in general, shedding further light on some older ideas discussed by Binford (1982).

Analogue models: In contrast to the pure rule-based logic of mathematical models, analogue models explicitly use information from better known or empirically documented situations (e.g. experiment or ethnography) to generate predictions. It is this sense of analogy between one set of empirical phenomena and another from which this subset of models takes its name.

In general, the line between many testable hypotheses (see above) and analogue models will be very fine if not somewhat false. However, a useful distinction is to consider analogue models as heuristic instruments that go further than a hypothesis and use some *constructed* device – either a diagram, set of numerical figures (e.g. independent data matrix) and/or explicit logical sequence – to help formulate predictions. Construction of such a device may itself involve some analytical component (e.g. cluster analysis of ecological, geographical or temporal parameters) or combine *a priori* empirical knowledge and logic – the theoretical and empirical underpinnings of which should, of course, be made explicit. Analogue models will be most powerful when predictions derived from them can be tested using inferential statistical procedures (i.e. goodness-of-fit can be assessed as statistically significant or non-significant at $p \leq 0.05$).

In this volume, Shott provides a demonstration of analogue model use. Shott compares reduction/curation distributions of Palaeoindian bifaces against quantitative and graphic models (survivorship curves) more typically applied in the study of population demography. Hence, these analyses aptly illustrate the principle of

taking empirical knowledge about how phenomena react in one sphere and applying it another to help provide an understanding of data patterning. Braun and colleagues also take advantage of such models in their analysis of Oldowan material from Koobi Fora (Kenya), which draws attention to the fact that models of this nature may be of utility in a wide variety of geographical and chronological settings.

Lycett also utilises several examples of analogue model. In one of his analyses, an analogue model is used to determine whether patterns produced via a cladistic analysis of Acheulean handaxes may be reflecting raw material factors rather than phylogenetic patterns influenced by social transmission processes. He builds a "model tree" based on the raw material of the assemblages concerned and compares the shapes of this tree statistically against those produced during the cladistic analysis. The logic being used here is that if the cladistic patterns are not significantly different from those based purely on raw material, then it may be taken that raw material is having a dominant influence on the "phylogenetic" patterns produced. Conversely, if the raw material model tree is statistically different from the cladogram, then raw material factors may be confidently rejected as a dominant cause of the patterns displayed.

Null models: Null models comprise the simplest (i.e. most parsimonious) explanations for a given data pattern. The strength of this form of model lies in the fact that if not rejected, the model adequately explains the data and more complex scenarios (however intuitively appealing) cannot be given intellectual priority.

Stochastic (i.e. random or "neutral") models are a specific type of null model, and arguably the most well known (although it should be emphasised that not all null models invoke stochasticity as the means of appealing to parsimony). Stochastic models are truly "null" in the sense that they take randomness as the default position: only when a deviation from randomness is found is there any need to begin seeking alternative explanations for the observed "pattern". Some of these models may be expressed as mathematical functions, such as the Lévy Walk model used by Grove discussed above.

In recent years, null models have become more common in studies of lithic data. For instance, Brantingham (2003) has shown that raw material selectivity can be modelled in a "neutral" or random sense. Hence, if the use of raw material in a given region conforms to the patterns of the neutral model there is no need to invoke tactical decision-making processes concerning raw material use. If, however, the pattern of raw material use does not conform to the parameters of the neutral model, tactical raw material usage may confidently be invoked. In the current volume, Braun also draws on such logic in his analysis of material from Koobi Fora.

In sum, models are formed *a priori* for a specific purpose. As with the word "analytical", the term "model" has frequently been misused, especially as a synonym for a "theory" that is usually derived (post-hoc) from a narrativical discussion of a set of "data". As should be apparent from the foregoing, a formal analytical model must be far more than this and is employed tactically in a very different manner. That is, they form a structured link between a set of theoretical parameters and predicted empirical patterns. It might be easy to look at some analytical models and suggest they are too simplistic or do not account for "everything". However, such statements are based on misunderstandings concerning the role of models as a means of analytical procedure, and the nature of the predictions derived from the theoretical parameters

on which they are based. Models are not by themselves statements about reality; rather they are formalised means of laying down explicit parameters in order that we can ask *how much does reality match this pattern*? Sometimes it will match the pattern with high degrees of fit; on other occasions, it will not match the data very well at all. Either way, we have made a manifest advance in our knowledge, being able to rule out or confirm the role of specific parameters and their strength of influence over a set of known variables.

Cultural Transmission and Lineages of Artefactual Traditions

> *[T]he production of a concomitant set of artefacts constitutes the transmission of information or message … A child brought up amongst motor-cars and skyscrapers is differently informed to another child born amongst stone axes and pig hunts*
>
> D.L. Clarke (1968: 86).

In recent years there has been a resurgence and growth of interest in issues of social transmission, the study of artefact lineages (i.e. diachronic "traditions") and cultural phylogenetics (see e.g. O'Brien and Lyman 2000, 2003; Mace et al. 2005; Lipo et al. 2006; O'Brien 2008; Shennan 2000, 2009; Mesoudi et al. 2004, 2006). Quite correctly, such work frequently gives credit to the writings of figures such as Cavalli-Sforza and Feldman (1981) and Boyd and Richerson (1985) as sources of inspiration. As others have highlighted, however, such issues in the case of archaeological artefacts were of specific concern to David Clarke (e.g. Shennan 1989, 2004; O'Brien and Lyman 2000). Hence, somewhat ironically, despite being considered as part of the essential textual canon of the "New Archaeology", Clarke's (1968) own work continued to address issues more commonly associated with the preceding "culture-historical" approach, which of course was much maligned by what later became to be known as "Processual Archaeology" (Shennan 1989, 2004). In this sense, Clarke's own version of "New Archaeology" was distinctive from that of others, and much of the current archaeological interest in issues of cultural transmission and the phylogenetics of tradition owes something of its heritage both to culture history and to Clarke's *Analytical Archaeology* (O'Brien and Lyman 2000; Shennan 2000, 2004).

Contemporary "cultural evolutionary" approaches are based on three keystones: the social transmission of information (i.e. a mode of inheritance), variation in transmitted phenomena, and the subsequent sorting of variation which results in the unequal transmission of given variants through time (Eerkens and Lipo 2007). Figure 1.2a–c shows three modified versions of illustrations taken from *Analytical Archaeology*, which are particularly demonstrative of Clarke's (1968) presaging of many issues perhaps only recently examined in earnest by those working in the cultural evolution or "evolutionary archaeological" framework. Despite this Clarkeian ancestry, it is of course important to emphasise both the recent theoretical expansion of such a framework (frequently through empirical case studies) and the expansion of its analytical toolkit (Shennan 2004), the latter of which has frequently

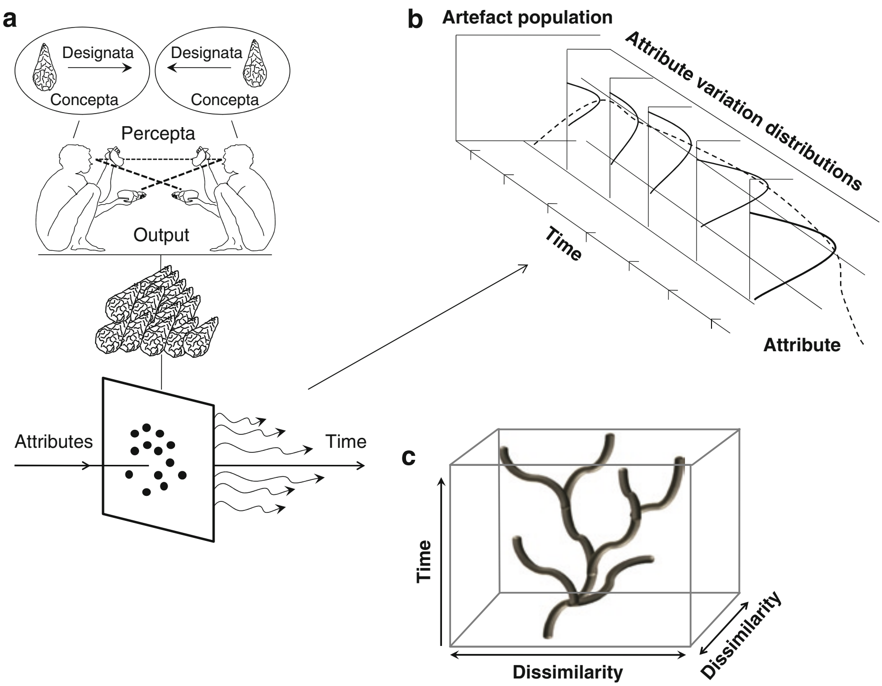

Fig. 1.2 (**a**–**c**) The concepts of social transmission, attribute variability in artefacts (and the sorting of such variation through time), and the creation of tradition lineages and cultural phylogenies, as envisioned by Clarke (1968). (**a**) The knapper possesses a set of concepts, ideas, craft skills, and knowledge that are employed in the manufacture of stone artefacts (*Concepta*). The artefacts are used in a set of roles or activities thus engaging with environment and context (*Designata*). The relationship between *Designata* and *Concepta* may be reciprocal. When learning a craft skill, the manufacturer is – via a process of social interaction – influenced by others, who in turn are ultimately influenced by the cumulative *Designata* and *Concepta* of previous generations. The artefacts produced vary within and between themselves in terms of a series of attributes. (**b**) Different attributes will have differing means, modes and standard deviations, and in turn these will vary within assemblages at different times. (**c**) The variations of attributes will change differently in different populations through time. This will lead to a diversification and branching of tradition lineages through time creating cultural phylogenies. (Redrawn and modified from Clarke 1968 (**a**) Fig. 39, p. 182; (**b**) Fig. 33, p. 171; (**c**) Fig. 20, p. 147. For definitions of *Designata*, *Concepta*, and *Percepta*, see Clarke 1968, p. 649)

drawn on techniques used to examine cognate issues in biology and palaeontology (O'Brien and Lyman 2000, 2003; Collard and Shennan 2000; Lycett, this volume). Theoretical expansions include greater emphasis on demographic factors affecting differential variant sorting through time (e.g. Lipo et al. 1997; Shennan 2000, 2001; Henrich 2004; Shennan and Bentley 2008; Lycett and Norton 2010), especially in regard to stochastic sorting mechanisms (i.e. "drift") (e.g. Neiman 1995; Shennan 2001; Lycett 2008; Hamilton and Buchanan 2009). Additionally, more recent authors have tended to make explicit distinctions between cultural selection (both

conscious and unconscious varieties which may – but do not *necessarily* – affect biological fitness) and natural selection mechanisms operating on fitness directly (Cavalli-Sforza and Feldman 1981; Eerkens and Lipo 2005; Shennan 2006; for a discussion of these issues in relation to Palaeolithic artefacts see Lycett 2008).

Several chapters in the current volume discuss issues of social transmission and concepts of tradition in Palaeolithic technologies. Clarkson, for instance, argues that cores might preserve particularly high levels of information concerning the social transmission of technological traditions. As noted earlier, Clarkson tests directly the hypothesis that raw material is the dominant influence on the attributes of cores from the Howiesons Poort MSA of southern Africa, using a multivariate framework. In fact, Clarkson finds that using geographical region as a grouping variable actually results in higher classification scores than raw material, suggestive that regionally specific social traditions involved in core reduction are indeed preserved in the morphological attributes of cores from this period. Buchanan and Collard's analyses similarly suggest that changes in Palaeoindian point morphology due to resharpening do not necessarily negatively impact classification scores. This leads them to conclude that resharpening techniques themselves, and/or socially held ideas surrounding blade shape, were influenced by factors that could have been influenced by cultural transmission. Lycett, meanwhile, discusses more fully the idea that methods and models used in biological settings to study the transmission of genetic patterns between generations can be constructively used in the analysis of Palaeolithic data.

Morphometrics

Put simply, *morphometrics* is the application of geometrical principles to the statistical study of morphology (Dryden and Mardia 1998). It bears repeating that every observation about the form of a stone artefact is an exercise in the description of morphology. Equally, knapped stone artefacts are – by definition – the product of hominin action interacting with a given raw material. In turn, accurate and detailed observations of stone tool form should lead us toward an increased understanding of both within-assemblage and between-assemblage variation, as well as the factors that lead to such variability, whether this be stochasticity, raw material, reduction intensity, function, ecology, cultural tradition, and cognitive and/or biomechanical differences.

As Clarke (1968: 528–530) recognised, in a practical sense, some of the problems involved in the quantitative process of artefact description are cognate to problems faced by biologists in the description of organismal form. In palaeontology (and biology in general) powerful mathematical and statistical methods of analysis are now routinely applied to detailed morphometric data sets, which allow secure assessments of intra- and inter-taxonomic variability, at both regional and global levels (e.g. O'Higgins 2000). Increased use of more sophisticated approaches

to size adjustment (such that size may be analytically disentangled from shape; see e.g. Jungers et al. 1995; Falsetti et al. 1993), along with increased use of geometric morphometric methods in both 2D and 3D have led to what some have termed a "revolution" in biological morphometrics in recent decades (Adams et al. 2004; Jensen 2003; Rohlf and Marcus 1993).

In retrospect, therefore, it might be regarded as remarkably prescient of Clarke (1968: 528–530) that toward the end of *Analytical Archaeology* he included a picture and description of a "d-mac" tracer, which he believed could be of utility for the morphometric analysis of archaeological artefacts. He further wrote (1968: 530) of the future role of digitisation and scanning equipment, which in combination with computer technology, he suggested "are about to revolutionise the standard approaches". Equally, prescient, however, he wrote "but [these] will doubtless take some time to infiltrate into archaeological studies" (1968: 530). Nevertheless, we might contend that even Clarke would be both surprised and disappointed to see just how long it has taken for archaeology to more seriously engage with these issues and methods.

As Costa and Ioviţă note in their respective chapters of this volume, morphometric approaches to lithic analysis have been employed by archaeologists for several decades, yet the extent of these approaches (both in terms of number of variables and number of artefact "morphs" studied within a single framework) has remained somewhat limited. In the case of the Lower Palaeolithic, for instance, other than some basic dimensions taken on flakes, the Bordes/Roe/Isaac system of biface measurements (e.g. Bordes 1961; Roe 1968; Isaac 1977) remains one of the few widely applied methodologies, yet is not easily adapted to allow the contiguous study of a wider range of artefacts. This, we are at pains to stress, does not mean such a system is without great value; many valuable insights into artefactual variation have been elicited via the use of such systems (e.g. Crompton and Gowlett 1993; Gowlett et al. 2001; McPherron 1999, 2003; White 1998; Brooks et al. 2006; Norton et al. 2006),[3] and several studies in this volume make creative use of simple measurement data (Shott, Chauhan). Indeed, we might argue that *not enough* studies have utilised even straightforward methodologies such as this. Rather, what we would contend is that it is only until relatively recently that lithic analysts began to explore the potential of more sophisticated approaches to the description and analysis of stone tool form. Such contrasts are especially stark when compared with morphometric developments that have taken place, for example, in Palaeolithic archaeology's sister disciple of physical anthropology (Slice 2007).

Several potential reasons for the relatively slow adoption of more sophisticated morphometric methods in lithic studies might be offered. One is simply the difficulties of using expensive precision and digital equipment in conjunction with the high levels of dust and grit that are frequently associated with lithic collections,

[3] See Wynn and Tierson (1990) for a rare example of a methodology that attempts to go beyond the standard measurement scheme for bifaces.

both in the field and lab (e.g. McPherron and Dibble 2003). A further reason might be the general suspicion and lack of interest mentioned earlier that is sometimes associated with quantitative methods, as might the lack of relevant training. However, while such reasons might have been in operation, we suspect these are less pertinent than a more fundamental problem. In the case of biological forms (especially skeletal structures), there are frequently a large number of readily identifiable points of correspondence, or "homologous landmarks" (e.g. the junctions of cranial sutures), which can be seen across a range of different taxa, even in the face of what might sometimes be quite disparate morphologies. Sadly, this cannot be said so easily in the case of stone artefacts, as both Iovіţă, and Monnier and McNulty note in this volume.

A concept of correspondence or "homology" (i.e. that the features being measured in one specimen are directly analogous to those measured in another) is of course crucial to any morphometric analysis.[4] In the field of biology, the ready identification of suitable landmarks enables the calculation of multiple inter-landmark distances, which can subsequently be size-adjusted [e.g. by the geometric mean (Jungers et al. 1995)] in order to create shape variables. Such variables may then be analysed using a variety of parametric and multivariate statistics. Alternatively, landmark coordinates may be analysed via a *geometric morphometrics* framework. Geometric morphometrics is the analysis of landmark configurations following standardization of their orientation, position and scaling (Slice 2007). Several freely available programs are now available for this purpose.[5] The resulting shape variables can then be inputted to a multivariate statistical analysis.

The lack of easily defined points of homology on stone artefact forms is thus debilitating to the straight forward application of several morphometric methodologies seen in other fields. As Iovіţă notes in this volume, lithic analysts have been inventive in overcoming some of these impediments in recent years (Buchanan 2006; Clarkson et al. 2006; Lycett et al. 2006), and the contributors to this volume present a range of solutions to this problem. Several contributors here for example use what are termed "semilandmark" approaches (Buchanan and Collard, Costa, Monnier and McNulty). Terminologically, Bookstein (1991: 63–66) originally identified three categories of landmark. Type I landmarks were those readily identifiable points (e.g. cranial suture junctions) that required no geometric definition in relation to other aspects of the specimen. Type II landmarks were identified as morphologically isolated points or extremities (e.g. the tips of extrusions or invaginations). Type III landmarks were regarded as geometrically defined points, and thus are identified instrumentally. An important point here is that "homology" is not

[4] Confusingly, the term "homology" has several distinct meanings in both biology and archaeology (Lycett 2009). Use of the term "homology" in the sense of landmark correspondence across forms should not be confused with "phylogenetic homology" resulting from shared ancestry (see O'Brien, this volume).

[5] See e.g., http://life.bio.sunysb.edu/morph/

necessarily an inherent or conveniently identifiable property, but something that may emerge from a clear but operationally specified definition (O'Higgins 2000). Subsequently, Bookstein (1997) renamed Type III landmarks as "semilandmarks". Semilandmarks can conceptually be thought of as homologous in the sense of being *geometrically* correspondent across forms. Hence, via the use of explicit geometric protocols for their identification, the locations of semilandmarks are driven by the observed morphology, thus effectively capturing morphological similarities and disparities across specimens.

In addition to semilandmark methods, Iovişă points out the utility of outline methods – in this case *Fourier analysis* – as a means of overcoming landmarking issues in the case of stone tools. As Iovişă notes, given that many questions concerning stone tool form might be addressed via an examination of outlines, it is somewhat surprising that archaeologists have not made more extensive use of such methods. Meanwhile, Clarkson and Lycett show in their respective chapters how a range of quantitative attributes, including several with a long history in lithic studies, can be employed alongside novel attributes in multivariate frameworks of analysis. Clarkson's chapter includes discussion of how core angles may be captured quantitatively using digitizing equipment (*Microscribe*™, Immersion Corp., San Jose, USA) more typically used for capturing landmark data (see also Clarkson et al. 2006). In a similar vein, Braun and colleagues describe a method for capturing flake platform areas using such equipment. These examples show that the use of new morphometric procedures in contemporary lithic analysis involves not only the adoption of existing methods employed in other fields (as useful as that may be) but is also creatively finding new means of addressing problems unique to the study of stone artefacts.

In sum, the judicious use of new morphometric methods may open novel lines of enquiry, allowing stone artefact parameters to be quantified more extensively and more accurately than ever before. It must be remembered, of course, that morphometrics is no panacea for the problems faced by lithic analysts; we must still be measuring analytically relevant variables (Lycett 2009; Braun this volume). However, it must be equally remembered that what gives a variable relevancy is not inherent properties *per se*, but the construction of a theory or model that allows patterns created by measurement procedures to be compared for goodness-of-fit or statistical significance, in line with the predictions of the hypothesis or model (Clarke 1968; Hill 1972). Rather, given that artefacts are – by definition – the product of human action, the number of variables that are analytically *irrelevant* can only be determined in the context of the analytical framework used. A more immediately pressing concern might therefore be the construction of testable hypotheses and models, whether these are dependent upon prior observations, ethnology, ethnography, experiment, or evolutionary, ecological and social theory. What morphometric methods do, we would contend, is open up the range of possibilities in which lithic analysts can relate such hypotheses and models to empirical data.

Along with an ensemble of recent work (e.g. Saragusti et al. 2005; Buchanan 2006; Clarkson et al. 2006; Lycett et al. 2006; Lycett 2007; Iovişă 2009), we believe the

chapters in this book are indicative that a "revolution" in lithic morphometrics is in progress, equivalent to the one undergone in biology in recent decades (Jensen 2003; Rohlf and Marcus 1993), and along the lines envisioned by Clarke over four decades ago. In the case of the Palaeolithic, there is often an emphasis on obtaining new data via new fieldwork, and of course such endeavours are essential to the discipline. However, in physical anthropology countless students and professionals set out year after year to measure the same primate and human skeletal collections, yet all are tackling different questions, often with a variety of methods. Many lithic collections derived from field survey and excavation currently languish in universities and museums around the world. An increase in morphometric studies may further increase (and encourage) greater analytical potential to be derived from such collections, thus extending their value as research resources.

Conclusions

The current volume has two sides. On the one hand, several innovative techniques and novel perspectives are presented. Yet on the other, they appear to be guided by certain general philosophical principles whose origin in the discipline can be traced, at least in part, to a volume (Clarke 1968) published at a date prior to which the majority of contributors to this volume were even born.[6]

It is probable that disagreements on certain finer points are evident in the views of some contributors. However, we believe there is sufficient common ground under the general philosophical approach taken by the contributors that even such disagreements are providing fruitful future lines of enquiry rather than descending into irresolvable polemic. The "general philosophical approach" we speak of is, of course, one guided by formal analysis, hypothesis testing, model building, quantification and statistical approaches. These are themes that we believe David Clarke would recognise, and we hope, be content to see them in active operation today during the analysis of Palaeolithic data. For via their application, it appears that new perspectives on old stones may emerge.

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[6] In the interests of discretion, we will leave it to the reader to work out for themselves which authors do not fall into this category!

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References

Adams, D.C., Rohlf, F.J. and Slice, D.E., 2004. Geometric morphometrics: ten years of progress following the ‘revolution’. *Italian Journal of Zoology* 71: 5–16.

Andrefsky, W., 1998. *Lithics: Macroscopic Approaches to Analysis*. Cambridge University Press, Cambridge.

Binford, L.R., 1982. The archaeology of place. *Journal of Anthropological Archaeology* 1: 5–31.

Bookstein, F.L., 1991. *Morphometric Tools for Landmark Data: Geometry and Biology*. Cambridge University Press, Cambridge.

Bookstein, F.L., 1997. Landmark methods for forms without landmarks: morphometrics of group differences in outline shape. *Medical Image Analysis* 1: 225–243.

Bordes, F., 1961. *Typologie de Paléolithique Ancien et Moyen*. Delmas, de l’Université de Bordeaux 1. Bordeaux.

Boyd, R. and Richerson, P., 1985. *Culture and the Evolutionary Process*. University of Chicago Press, Chicago.

Brantingham, P.J., 2003. A neutral model of stone raw material procurement. *American Antiquity* 68: 487–509.

Brooks, A.S., Nevell, L., Yellen, J.E. and Hartman, G., 2006. Projectile technologies of the African MSA. In *Transitions Before the Transition: Evolution and Stability in the Middle Palaeolithic and Middle Stone Age*, edited by E. Hovers and S. L. Kuhn, pp. 233–255. Springer, New York.

Brown, CT., Liebovitch, L.S. and Glendon, R., 2007. Levy flights in Dobe Ju/’hoansi foraging patterns. *Human Ecology* 35: 129–138.

Buchanan, B., 2006. An analysis of Folsom projectile point resharpening using quantitative comparisons of form and allometry. *Journal of Archaeological Science* 33: 185–199.

Cavalli-Sforza, L.L. and Feldman, M.W., 1981. *Cultural Transmission and Evolution: A Quantitative Approach*. Princeton University Press, Princeton, NJ.

Clarke, D.L., 1968. *Analytical Archaeology*. Methuen, London.

Clarke, D.L., 1972. Models and paradigms in contemporary archaeology. In *Models in Archaeology*, edited by D. L. Clarke, pp. 1–60. Methuen, London.

Clarkson, C., Vinicius, L. and Lahr, M.M., 2006. Quantifying flake scar patterning on cores using 3D recording techniques. *Journal of Archaeological Science* 33: 132–142.

Collard, M. and Shennan, S., 2000. Processes of cultural change in prehistory: a case study from the European Neolithic. In *Archaeogenetics: DNA and the Population Prehistory of Europe*, edited by C. Renfrew and K. Boyle, pp. 89–97. McDonald Institute for Archaeological Research, Cambridge.

Crompton, R.H. and Gowlett, J.A.J., 1993. Allometry and multidimensional form in Acheulean bifaces from Kilombe, Kenya. *Journal of Human Evolution* 25: 175–199.

Dryden, I.L. and Mardia, K.V., 1998. *Statistical Shape Analysis*. Wiley, New York.

Eerkens, J.W. and Lipo, C.P., 2005. Cultural transmission, copying errors, and the generation of variation in material culture and the archaeological record. *Journal of Anthropological Archaeology* 24: 316–334.

Eerkens, J.W. and Lipo, C.P., 2007. Cultural transmission theory and the archaeological record: context to understanding variation and temporal changes in material culture. *Journal of Archaeological Research* 15: 239–274.

Eren, M., Greenspan, A. and Sampson, C.G., 2008. Are Upper Paleolithic blade cores more productive than Middle Paleolithic discoidal cores? A replication experiment. *Journal of Human Evolution* 55: 952–961.

Falsetti, A.B., Jungers, W.L., and Cole III, T.M., 1993. Morphometrics of the Callitrichid forelimb: a case study in size and shape. *International Journal of Primatology* 14: 551–572.

Flenniken, J.J. and Raymond, A.W., 1986. Morphological projectile point typology: replication experimentation and technological analysis. *American Antiquity* 51: 603–614.

Gibbon, G., 1984. *Anthropological Archaeology*. Columbia University Press, New York.

Goodman, M.E., 1944. The physical properties of stone tool materials. *American Antiquity* 9: 415–433.

Gowlett, J.A.J., Crompton, R.H. and Yu, L., 2001. Allometric comparisons between Acheulean and Sangoan large cutting tools at Kalambo Falls. In *Kalambo Falls Prehistoric Site: Volume III*, edited by J. D. Clark, pp. 612–619. Cambridge University Press, Cambridge.

Hair, J.F., Anderson, R.E., Tatham, R.L. and Black, W.C., 1998. *Multivariate Data Analysis*. Fifth Edition. Prentice-Hall, Upper Saddle River, NJ.

Hamilton, M.J. and Buchanan, B., 2009. The accumulation of stochastic copying errors causes drift in culturally transmitted technologies: quantifying Clovis evolutionary dynamics. *Journal of Anthropological Archaeology* 28: 55–69.

Hammond, N., 1979. David Clarke: a biographical sketch. In *Analytical Archaeologist: Collected Papers of David L Clarke*, pp. 1–10. London: Academic Press.

Henrich, J., 2004. Demography and cultural evolution: how adaptive cultural processes can produce maladaptive losses – the Tasmanian case. *American Antiquity* 69: 197–214.

Hill, J.N., 1972. The methodological debate in contemporary archaeology: a model. In *Models in Archaeology*, edited by D. L. Clarke, pp. 61–107. Methuen, London.

Hiscock, P. and Clarkson, C., 2005. Experimental evaluation of Kuhn's geometric index of reduction and the flat-flake problem. *Journal of Archaeological Science* 32: 1015–1022.

Ioviţă, R.P., 2009. Ontogenetic scaling and lithic systematics: method and application. *Journal of Archaeological Science* 36: 1447–1457.

Isaac, G.L., 1977. *Olorgesailie: Archaeological Studies of a Middle Pleistocene Lake Basin in Kenya*. University of Chicago Press, Chicago.

Jensen, R.J., 2003. The conundrum of morphometrics. *Taxon* 52: 663–671.

Jungers, W.L., Falsetti, A.B. and Wall, C.E., 1995. Shape, relative size, and size adjustments in morphometrics. *Yearbook of Physical Anthropology* 38: 137–161.

Kitching, I.J., Forey, P.L., Humphries, C.J. and Williams, D.M., 1998. *Cladistics: The Theory and Practice of Parsimony Analysis*. Second Edition. Oxford University Press, Oxford.

Kooyman, B.P., 2000. *Understanding Stone Tools and Archaeological Sites*. University of New Mexico Press, Albuquerque.

Lipo, C.P., Madsen, M.E., Dunnell, R.C. and Hunt, T., 1997. Population structure, cultural transmission, and frequency seriation. *Journal of Anthropological Archaeology* 16: 301–333.

Lipo, C.P., O'Brien, M.J., Collard, M. and Shennan, S. (Eds.), 2006. *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory*. Aldine Transaction, New Brunswick, NJ.

Lycett, S.J., 2007. Is the Soanian techno-complex a Mode 1 or Mode 3 phenomenon? A morphometric assessment. *Journal of Archaeological Science* 34: 1434–1440.

Lycett, S.J., 2008. Acheulean variation and selection: does handaxe symmetry fit neutral expectations? *Journal of Archaeological Science* 35: 2640–2648.

Lycett, S.J., 2009. Quantifying transitions: morphometric approaches to Palaeolithic variability and technological change. In *Sourcebook of Palaeolithic Transitions: Methods, Theories, and Interpretations*, edited by M. Camps and P. R. Chauhan, pp. 79–92. Springer, New York.

Lycett, S.J. and Norton, C.J., 2010. A demographic model for Palaeolithic technological evolution: the case of East Asia and the Movius Line. *Quaternary International* 211: 55–65.

Lycett, S.J., von Cramon-Taubadel, N. and Foley, R.A., 2006. A crossbeam co-ordinate caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33: 847–861.

Mace, R., Holden C.J. and Shennan S. (Eds.), 2005. *The Evolution of Cultural diversity*. UCL Press, London.

Machin, A.J., Hosfield, R.T. and Mithen, S.J., 2007. Why are some handaxes symmetrical? Testing the influence of handaxe morphology on butchery effectiveness. *Journal of Archaeological Science* 34: 883–893.

McPherron, S.P., 1999. Ovate and pointed handaxe assemblages: two points make a line. *Préhistoire Européenne* 14: 9–32.

McPherron, S.P., 2003. Technological and typological variability in bifaces from Tabun Cave, Israel. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H. L. Dibble, pp. 55–75. University of Pennsylvania, Philadelphia, PA.

McPherron, S.P. and Dibble, H.L., 2003. Using computers in adverse field conditions: tales from the Egyptian desert. *SAA Archaeological Record* 3: 28–32.

Mesoudi, A., Whiten, A. and Laland, K.N., 2004. Is human cultural evolution Darwinian? Evidence reviewed from the perspective of *The Origin of Species*. *Evolution* 58: 1–11.

Mesoudi, A., Whiten, A. and Laland, K.N., 2006. Towards a unified science of cultural evolution. *Behavioral and Brain Sciences* 29: 329–383.

Neiman, F.D., 1995. Stylistic variation in evolutionary perspective: inferences from decorative diversity and interassemblage distance in Illinois Woodland ceramic assemblages. *American Antiquity* 60: 7–36.

Norton, C.J., Bae, K., Harris, J.W.K. and Lee, H., 2006. Middle Pleistocene handaxes from the Korean Peninsula. *Journal of Human Evolution* 51: 527–536.

O'Brien, M.J., 2008. *Cultural Transmission and Archaeology: Issues and Case Studies*. Society for American Archaeology Press, Washington, DC

O'Brien, M.J. and Lyman, R.L., 2000. *Applying Evolutionary Archaeology: A Systematic Approach*. Kluwer Academic/Plenum, New York.

O'Brien, M.J. and Lyman, R.L., 2003. *Cladistics and Archaeology*. University of Utah Press, Salt Lake City, UT.

O'Brien, M.J., Lyman, R.L. and Schiffer, M.B., 2005. *Archaeology as a Process: Processualism and Its Offspring*. University of Utah Press, Salt Lake City.

O'Higgins, P., 2000. The study of morphological variation in the hominid fossil record: biology, landmarks and geometry. *Journal of Anatomy* 197: 103–120.

Patten, B., 2005. *Peoples of the Flute: A Study in Anthropolithic Forensics*. Stone Dagger Publications, Denver, CO.

Quinn, G. P. and Keough, M.J., 2002. *Experimental Design and Data Analysis for Biologists*. Cambridge University Press, Cambridge.

Roe, D.A., 1968. British Lower and Middle Palaeolithic handaxe groups. *Proceedings of the Prehistoric Society* 34: 1–82.

Rohlf, F.J. and Marcus, L.F., 1993. A revolution in morphometrics. *Trends in Ecology and Evolution* 8: 129–132.

Saragusti, I., Karasik, A., Sharon I. and Smilansky, U., 2005. Quantitative analysis of shape attributes based on contours and section profiles in artifact analysis. *Journal of Archaeological Science* 32: 841–853.

Shea, J.J., Davis, Z. and Brown, K., 2001. Experimental tests of Middle Palaeolithic spear points using a calibrated crossbow. *Journal of Archaeological Science* 28: 807–816.

Shennan, S., 1989. Archaeology as archaeology or as anthropology? Clarke's *Analytical Archaeology* and the Binfords' *New Perspectives in Archaeology* 21 years on. *Antiquity* 63: 831–835.

Shennan, S., 1997. *Quantifying Archaeology*. Second Edition. Edinburgh University Press, Edinburgh.

Shennan, S., 2000. Population, culture history, and the dynamics of culture change. *Current Anthropology* 41: 811–835.

Shennan, S., 2001. Demography and cultural innovation: a model and its implications for the emergence of modern human culture. *Cambridge Archaeological Journal* 11: 5–16.

Shennan, S., 2004. Analytical archaeology. In *A Companion to Archaeology*, edited by J. Bintliff, pp. 3–20. Blackwell, Oxford.

Shennan, S., 2006. From cultural history to cultural evolution: an archaeological perspective on social information transmission. In *Social Information Transmission and Human Biology*, edited by J. C. K. Wells, S. Strickland and K. Laland, pp. 173–189. Taylor & Francis, New York.

Shennan, S. (Ed.), 2009. *Pattern and Process in Cultural Evolution*. University of California Press, Los Angeles.

Shennan, S.J. and Bentley, R.A., 2008. Style, interaction, and demography among the earliest farmers of central Europe. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M. J. O'Brien, pp. 164–177. Society for American Archaeology Press, Washington, DC.

Shott, M.J., Bradbury, A.P., Carr, P.J. and Odell, G.H., 2000. Flake size from platform attributes: predictive and empirical approaches. *Journal of Archaeological Science* 27: 877–894.

Sisk, M. and Shea, J., 2009. Experimental use and quantitative performance analysis of triangular flakes (Levallois points) used as Arrowheads. *Journal of Archaeological Science* 36: 2039–2047.

Slice, D.E., 2007. Geometric morphometrics. *Annual Review of Anthropology* 36: 261–281.

Stout, D., 2006. Oldowan toolmaking and hominin brain evolution: theory and research using Positron Emission Tomography (PET). In *The Oldowan: Case Studies into the Earliest Stone Age*, edited by N. Toth and K. Schick, pp. 267–299. Stone Age Institute, Bloomington, IN.

Stout, D. and Chaminade, T., 2007. The evolutionary neuroscience of tool making. *Neuropsychologia* 45: 1091–1100.

Stout, D., Toth, N. and Schick, K.D., 2000. Stone tool making and brain activation: Positron Emission Tomography (PET) studies. *Journal of Archaeological Science* 27: 1215–1223.

Stout, D., Toth, N. and Schick, K.D., 2006. Comparing the neural foundations of Oldowan and Acheulean toolmaking: a pliot study using Positron Emission Tomography (PET). In *The Oldowan: Case Studies into the Earliest Stone Age*, edited by N. Toth and K. Schick, pp. 321–331. Stone Age Institute, Bloomington, IN.

Toth, N., Schick, K.D. and Semaw, S., 2006. A comparative study of the stone tool-making skills of *Pan*, *Australopithecus*, and *Homo sapiens*. In *The Oldowan: Case Studies into the Earliest Stone Age*, edited by N. Toth and K. Schick, pp. 155–222. Stone Age Institute Press, Gosport, IN.

Trigger, B.G., 1989. *A History of Archaeological Thought*. Cambridge University Press, Cambridge.

White, M.J., 1998. On the significance of Acheulean biface variability in southern Britain. *Proceedings of the Prehistoric Society* 64: 15–44.

Wynn, T. and Tierson, F., 1990. Regional comparison of the shapes of later Acheulean handaxes. *American Anthropologist* 92: 73–84.

Chapter 2
A Geometric Morphometric Assessment of Plan Shape in Bone and Stone Acheulean Bifaces from the Middle Pleistocene Site of Castel di Guido, Latium, Italy

August G. Costa

Abstract Flaked bone artifacts are a noteworthy component of some Early and Middle Paleolithic tool kits. Several Paleolithic sites with lithic assemblages attributable to the Acheulean Industrial Complex (Mode 2) have yielded bifacial bone artifacts. Many of these bone implements are similar to classic handaxes in plan shape. The arbitrary imposition of form represented by these bone bifaces suggests the deliberate application of certain operational concepts that originate from particular Acheulean technological behaviors, namely, stone handaxe manufacture. In addition, the presence of these bone tools suggests an application of specific reductive techniques that originated in both Mode 1 (i.e., Oldowan) and Mode 2 (i.e., Acheulean) lithic technologies. How does the Acheulean model for stone biface shape compare to that observed for bone biface shape? In order to understand the degree to which Acheulean stone bifaces may have served as a model of form in flaked bone technology, an objective method for evaluating form is necessary. The dimensionless approach of geometric morphometrics was applied to the study of 2D bone and stone biface plan shape. The similarity of bone and stone bifaces from the Middle Pleistocene (~300 kya) Acheulean site Castel di Guido, Latium, Italy was evaluated by a geometric morphometric analysis of 2D outlines. The null hypothesis that there is no difference in the 2D shape of each artifact material class was tested by principal component analysis (PCA) and MANOVA/CVA of eigenshape scores. Results of the analysis show no significant difference between the plan morphology of bone and stone bifaces. These results may indicate that Acheulean concepts of preferred 2D shape were applied in the production of some bifacial bone tools and that a great disparity in raw materials did not significantly influence 2D biface morphology. Furthermore, these results lend support to the idea that Mode 2 stone flaking techniques and tool types were directly applied to bone materials in some instances.

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Introduction

Archaeological evidence shows that bone was, at least occasionally, a component of Paleolithic tool kits throughout the Quaternary (Backwell and d'Errico 2005; Patou-Mathis 1999; Villa and d'Errico 2001; Vincent 1993). Bone is a strong and flexible material that can be broken, ground, and shaped readily into various useful forms. The zooarchaeological record shows that animal remains were common among early meat-eating hominins (e.g., Blumenshine and Pobiner 2006; Domínguez-Rodrigo and Egeland 2007; Heinzelin et al. 1999), thus the technological exploitation of bone materials could have been an optimal behavior directly associated with subsistence. Consequently, the acquisition of bone materials may have been less energetically and cognitively demanding for hominins than locating and remembering the locations of lithic raw material sources. Although evidence of bone utilization is generally sparse in the Early and Middle Paleolithic, it is probable that the relatively poor preservation potential of bone artifacts is partially responsible. Overall, the Paleolithic evidence for bone tool use indicates that hominins frequently recognized bone as a useful substance and exploited it in several ways (Backwell and d'Errico 2005; Villa and d'Errico 2001).

The archaeological evidence for Paleolithic bone utilization (excluding percussors) may be organized into three groups. These groups can be ordered in a relative chronology and include: (1) bone tools unintentionally modified through use, (2) flaked bone tools, and (3) ground-bone tools. The first group is exemplified by the 1.8–1.1 million year old (mya) bone "digging-tools" from Swartkrans (Members 1–3) and Drimolen South Africa (Backwell and d'Errico 2004, 2005, 2008; Brain and Shipman 1993). The second group is best illustrated by flaked bone bifaces known from the Middle Pleistocene of Italy (Bidditu and Celletti 2001; Radmilli and Boschian 1996; Segre and Ascenzi 1984). Finally, the third group is well characterized by Late Pleistocene bone tools from the Middle Stone Age of Africa and the Upper Paleolithic of Western Europe (Henshilwood and Sealy 1997; Singer and Wymer 1982; Straus 1995; Yellen et al. 1995).

Paleolithic implements belonging to the flaked bone tool group are particularly interesting because they may represent the co-option of reductive techniques used in Mode 1 (core–flake) and Mode 2 (bifacial) lithic technologies (Villa and d'Errico 2001). The distribution of flaked bone technology is broad in time and space; however, most of the evidence associated with the Early Paleolithic is confined to the later Middle Pleistocene (0.5–0.2 mya) (Table 2.1). Although flaked bone tools are found throughout the Paleolithic, Early and Middle Pleistocene bone artifacts were rarely fashioned into consistent or systematic forms (Villa and d'Errico 2001). In a few rare cases, however, large bones were apparently shaped like the large bifacial cutting tools (specifically handaxes), characteristic of the Acheulean Industrial Complex (Backwell and d'Errico 2005; Bidditu and Celletti 2001; Bidditu and Segre 1982; Mallegni et al. 1983; Patou-Mathis 1999; Radmilli and Boschian 1996; Shipman 1989; Villa et al. 1999; Villa and d'Errico 2001).

The arbitrary imposition of shape evident in Acheulean bifaces such as the handaxe suggests the deliberate application of certain operational concepts (i.e., "mental

Table 2.1 A list of Early Paleolithic sites where flaked bone tools have been reported

Site	Age	No. of confirmed bifaces	References
Africa			
Olduvai Gorge FC Bed 2 (Tanzania)	1.7–1.2 mya	1	Leakey (1971)
Ternifine (Algeria)	~700 kya	0	Geraads et al. (1986)
Grotte des Ours (Morrocco)	>400 kya	0	Biberson (1961) and Clark (1977)
Near East			
Gesher Benot Ya'aqov, Israel	780 kya	0	Clark (1977) and Stekelis (1967)
Europe			
Bilzingsleben (Germany)	400–280 kya	1	Mania (1987)
Westfalen (Germany)	?	1	Günther (1988)
Verteszollos, (Hungary)	400–160 kya?	1	Dobosi (2001)
La Cotte de San Brelade (Jersey Island UK)	200–45 kya	0	Scott (1980, 1986a, b, 1989)
Italy			
Fontana Ranucchio	458 kya	~4	Bidditu et al. (1979), Bidditu and Celletti (2001) and Segre and Ascenzi (1984)
Castel di Guido	~300 kya	99	Mallegni et al. (1983), Mallegni and Radmilli (1988) and Radmilli and Boschian (1996)
Malagrotta	~300 kya	1	Cassoli et al. (1982)
La Polledrara di Cecanibbio	360–300 kya	0	Anzidei (2001) and Lemorini (2001)
Rebibbia-Casal de'Pazzi	240–180 kya	0	Anzidei (2001)
Cava Pompi	400 kya	0	Bidditu and Segre (1982)
Ceprano (Region)	>300 kya	0	Bidditu and Segre (1982)
Pontecorvo	300 kya?	0	Bidditu and Cassoli (1969)

Note that only a few sites have confirmed bone bifaces and many sites correspond to the temporal range of the Acheulean

templates," "rules," or "imperatives") toward target artifact forms (Clark 1994; Gowlett 2006; Toth and Schick 1993; Wynn 1995). In the case of stone Acheulean bifaces, it has even been suggested that traditions of manufacture may have created distinct regional patterns at broad levels (e.g., Wynn and Tierson 1990; Lycett and Gowlett 2008). The documentation of forms similar to those seen in stone examples among Early and Middle Paleolithic flaked bone tools raises the question of whether homologous concepts of target shape were applied in their manufacture. Although many bone bifaces are morphologically similar to stone bifaces, they have so far only been compared on a subjective basis. In order to test inferences about the co-option of Mode 2 flaking techniques and the target forms that bone bifaces may indicate, the similarities in form between these two artifact classes must be quantitatively demonstrated.

During the 1960s and 1970s, subjective evaluations of biface shape were supplanted by morphometric techniques that used linear measurements and derived ratios to quantify shape attributes (Callow 1976; Isaac 1977; Roe 1964, 1968). Even so, quantifying biface morphology has been a difficult task and traditional analytical methods reduce the complexity of overall biface shape (McPherron and Dibble 1999). For instance, 3D geometric morphometric analyses of Acheulean bifaces and other Early Paleolithic cores show that traditional analyses fail to capture significant shape variables that have real utility for lithic studies, beyond just classification (Lycett 2007; Lycett et al. 2006). Geometric morphometrics represents a promising new approach to the study of biface shape variability. Geometric morphometric methods are an effective way of illustrating variability in stone tool morphology and allow shape differences to be assessed independently of size (Brande and Saragusti 1999; Buchanan 2006; Lycett et al. 2006). Furthermore, geometric morphometric analyses may use digital data, such as images, which require less time and effort to collect than traditional metric data (McPherron and Dibble 1999). In sum, a geometric morphometric approach to the question of biface shape variability accounts for more idiosyncrasies in tool form while removing the influence of size and facilitating remote lithic studies with digital datasets.

The following study applies the objective approach of geometric morphometrics to the study of 2D bone and stone biface outline shape. In order to understand how the Acheulean target form of stone bifaces compares to that of bone bifaces, 2D plan outlines of these artifacts are used as a proxy for conceptual similarity. Synchronous stone and bone biface samples are compared from the Acheulean site of Castel di Guido, Italy to test the null hypothesis that there is no difference in the 2D shape of each artifact class. The null hypothesis may be falsified if a significant difference in the 2D shape of bone and stone bifaces is found. One might predict the latter to be the case because the influence of fracture mechanics in disparate raw material types may result in different 2D shapes. Alternatively, one would also expect the null hypothesis to be rejected if different shape plans (i.e., mental templates) or manufacturing strategies were applied to bone and stone bifaces. However, if the null hypothesis cannot be rejected and there is no difference in 2D biface shape, this similarity may be attributed to shared target forms (i.e., "mental templates," "rules," or "imperatives") or manufacturing strategies between the biface material classes.

Materials, Methods, and Predictions

Scanning

Outline data were obtained from the scans of 20 bone and 17 stone biface illustrations published in Radmilli and Boschian's 1996 monograph on Castel di Guido. The stone biface sample includes several different lithologies (e.g., chert, quartzite, and limestone), but these subgroups could not be differentiated with the published information. The bone materials are assumed to be essentially homologous, although it is likely that they

came from several different large mammalian taxa such as *Elephas antiquus* or *Bos primigenius* (Radmilli and Boschian 1996). In sum, this analysis makes the assumption that intraclass differences in raw material type (i.e., chert vs. flint and elephant vs. cow bone) and their potential influence on biface shape are minor relative to interclass differences (i.e., bone vs. stone).

Bone and stone biface illustrations from Radmilli and Boschian (1996) were scanned at 300 dpi with an Epson Stylus CX46000 flatbed scanner and processed in Adobe Photoshop CS. The bone biface sample was selected from illustrations depicting the external cortical bone surface only, as opposed to the internal medullary surface. Each biface was first outlined with Photoshop's magic wand tool and the background of each scan was then deleted to reduce noise. The latter step also insured that all biface outlines were without gaps. Any gaps in biface outline detected by the magic wand tool were closed with the Photoshop pencil tool utilizing a set thickness of 1 pixel to reduce artificial distortion. Finally, all bifaces were orientated in Photoshop so their tips pointed right and each modified scan was saved as a jpeg file.

Orientation Protocol

In any comparative morphometric analysis, it is essential that artifacts be orientated in a standardized manner so that comparisons between forms are (morphologically) homologous (Lycett et al. 2006). Several methods of orientating bifaces for comparative morphometric analyses have been discussed in the literature (McPherron and Dibble 1999). This study followed Callow's (1976) method of biface orientation (also described in McPherron and Dibble 1999). Following this procedure, all bifaces were oriented around their long axis of symmetry, so that the longest orthogonal lines drawn from a central line were equal in length (Fig. 2.1b). The biface tip was thus used as a landmark to anchor the central line. McPherron and Dibble (1999) found that this orientation method provided comparable results to other methods of orientating biface outlines so that overall bilateral symmetry was maximized.

Digitization and Formatting

Two thin-plate spline (tps) geometric morphometric data files were constructed for the bone and stone jpeg images using the program tpsUtility (Rohlf 2006a). Two-dimensional outlines of the bifaces were then digitized from the bone and stone tps files using the outline tool in the program tpsDig (Rohlf 2004). Outlines were automatically traced with the outline tool from the tip on the right side of each biface image (Fig. 2.1c). Defining the biface tip as a homologous landmark in all specimens facilitated subsequent geometric alignment of shape data (MacLeod 1999). Seventy-five equidistant points were recorded by each outline in tpsDig. This number of points reproduced

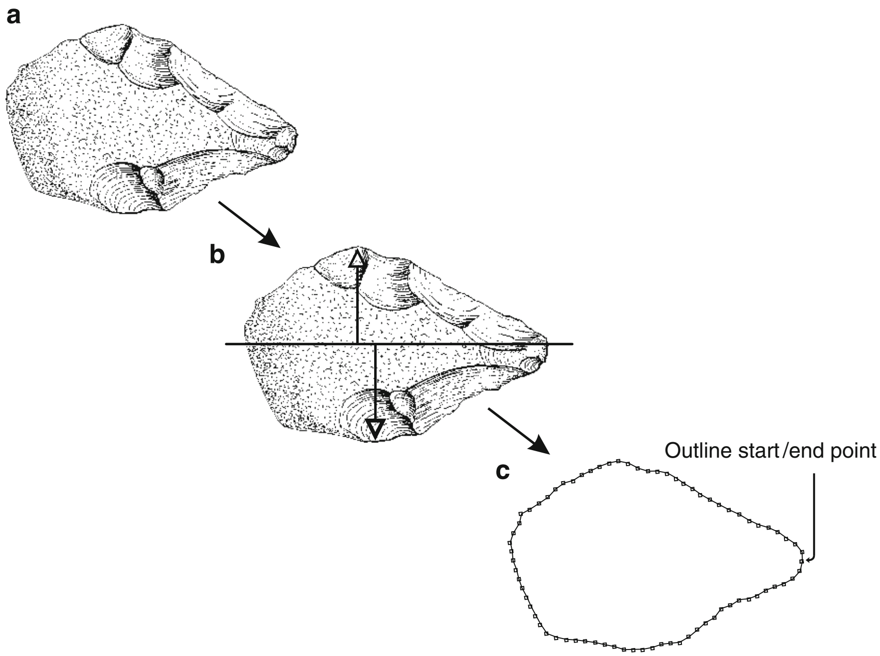

Fig. 2.1 Adjustment and acquisition of biface shape data. (**a**) Bitmap data from scans of biface illustrations were rotated 90° clockwise then (**b**) reoriented according to the technique described by Callow (1976). (**c**) Bitmap data were then transformed into Cartesian *XY* coordinate data in the form of a 2D biface outline with 75 equidistant points

biface shape with high fidelity. Following the digitization of all biface outlines in tpsDig, the bone and stone shape data were combined in tpsUtility. The shape data were then converted from outline to Cartesian *XY* landmark coordinates in tpsUtility.

Procrustes Fitting/Superimposition

The *XY* outline data file was opened in PAST (PAleontological STatistics), a program that may be used for the analysis of geometric morphometric data (Hammer et al. 2001). A 2D Procrustes superimposition of the *XY* outline coordinate data was performed and the consensus shape (i.e., sample mean) subtracted from all coordinates. This step effectively scales, rotates, and translates the *XY* coordinate data bringing all biface outlines to a standardized size, orientation, and position before subsequent analysis (Fig. 2.2) (Hammer and Harper 2006). Essentially, the shape coordinates are fitted around the centroid or group mean, which centers the specimen outlines on the origin (i.e., coordinate 0, 0). Subtracting the consensus shape or sample mean from the dataset ensures that principal component axes are centered at (0, 0) for subsequent PCA (Hammer and Harper 2006). Following the method described by

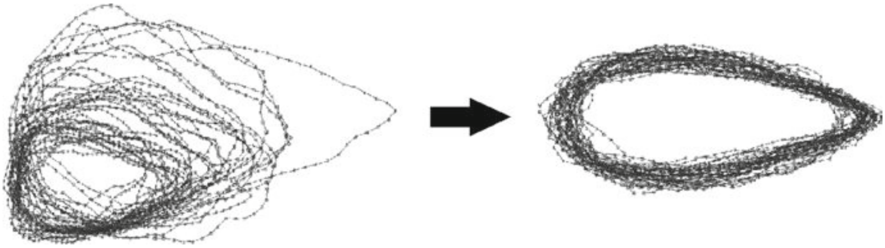

Fig. 2.2 The Procrustes superimposition process removes size, translation, and rotation (i.e., orientation) from the original shape data. Original outline data (*left*) vs. Procrustes aligned data (*right*)

Bailey and Byrnes (1990), intraobserver measurement error of this data acquisition methodology was 6.7%. Moreover, a test for significance of differences between replicate groups (five groups of five specimens each) yielded highly significant results ($p < 0.0001$), suggesting that shape differences were successfully measured by this method despite potential measurement error.

PCA of the Procrustes-adjusted *XY* outline data was implemented in PAST. This technique allowed the multivariate outline data to be projected into two dimensions so that the underlying shape variables could be examined and compared at a qualitative level (Hammer and Harper 2006). The principal component scores derived from the PCA also permitted a quantitative test of multivariate equality of means (MANOVA) between the two groups. One unshaped experimental bone specimen, illustrated by Backwell and d'Errico (2005, p.261), was included in the PCA for control purposes. This specimen was derived from an elephant limb bone and exhibits a biface-like plan shape, yet it reflects an initial blank form which has not been shaped through subsequent flaking in any way (Backwell and d'Errico 2005). If the Castel di Guido bone bifaces have been intentionally fashioned according to some target form, their 2D morphology should be different from this unmodified blank. Moreover, due to the fundamental differences in raw material type, one may further predict that the bone and stone bifaces will be well separated by lower-order principal components (PC 1–3) that explain a majority of the shape variance. However, if raw material differences have not significantly influenced 2D shape, one could predict that there might be overlap in principal component scatter plots.

Thin-Plate Spline Deformations

In order to interpret the meaning of the PCA results from a morphological perspective, Procrustes superimposed shape data were examined using tpsRelw, a geometric morphometric program designed for relative warps analysis (Rohlf 2006b). This program uses thin-plate splines to facilitate visualization of shape changes from the group mean along relative warp (i.e., principal component) axes (Hammer and

Harper 2006). In other words, this process allows estimated shape to be displayed at any point within a plot of any two principal components. This facilitated the translation of shape variation represented by the principal component axes into causative factors that may have affected artifact morphology.

Eigenshape Analysis

In order to ensure the reliability of morphometric results, raw outline data were subjected to an eigenshape analysis to test for MANOVA. This procedure served to replicate the MANOVA test on principal component scores utilizing a method that processes shape data differently. Eigenshape analysis is a technique used for the reduction of digitized outline shapes into a few parameters for multivariate analysis and visualization of shape variation (Hammer and Harper 2006). Eigenshape transforms *XY* outline coordinate data into shape functions by calculating the net deviance of tangent angles of adjacent points along the course of a digitized outline (Fig. 2.3) (MacLeod 1999). The sum of tangent angles in an outline constitute a vector describing the shape, which in this analysis is expressed as a circle-normalized net angular deviation (Phi star = ϕ^*)

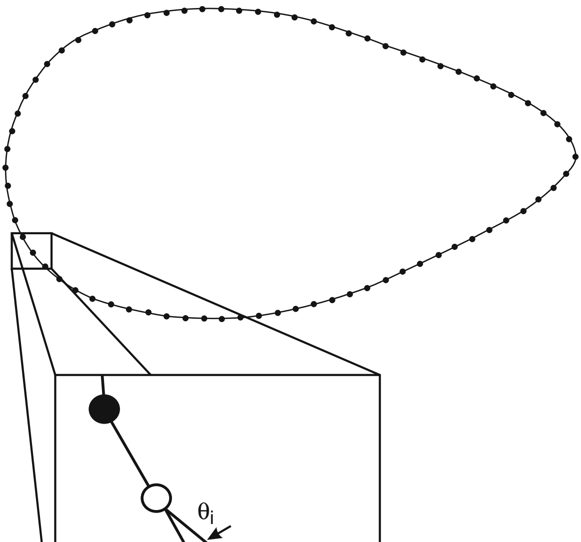

Fig. 2.3 The net angular deviation between adjacent *XY* coordinates in a biface outline that is transformed into a shape function during eigenshape analysis (after MacLeod 1999)

(Hammer and Harper 2006; MacLeod 1999). This normalization procedure has essentially the same effect as the Procrustes superimposition carried out in PAST for PCA allowing for dimensionless comparisons of shape to be made and evaluated with statistics. In the final step of eigenshape analysis, the variance–covariance matrix of the shape vectors is subjected to an eigenanalysis giving a number of principal components that are referred to as eigenshapes. This reduced shape data may then be exported to statistical software for further analysis (e.g., MANOVA).

Raw *XY* outline data were formatted in Microsoft Excel for Standard Eigenshape; a DOS program authored by Norman Macleod, which performs the eigenshape analytical procedure described above. The Standard Eigenshape program was used to convert raw *XY* outline date to eigenshapes that were subsequently imported into PAST for tests of MANOVA and canonical variate analysis (CVA). In PAST, MANOVA was used to test for the equality of multivariate means between the two groups while CVA is a discriminant option that produces a scatter plot of specimens along the first two canonical axes (i.e., those producing maximal and second to maximal separation between all groups) (Hammer and Harper 2006). As with the PCA, it was expected that the raw material differences would translate into significant 2D shape differences between the bone and stone biface groups. Therefore, in this analysis, it was predicted that the MANOVA test of group means (i.e., 2D shape centroids) would indicate a significant difference and CVA discriminating scatter plots would separate the two groups into distinct clusters, as assumed would occur in PCA.

Results

A qualitative examination of superimposed 2D outlines of both samples after Procrustes superimposition (i.e., with size removed) can give some indication of whether the shape model for these bifaces was similar or not (Fig. 2.4). Shape similarities and dissimilarities between the two samples are illustrated well by this simple comparison of the mean shape and specimen outlines of each group. On these grounds, the two biface groups do contrast slightly. The bone group appears more elongated and pointed relative to the stone sample, which is collectively broader and more ovate in form.

Principal Component Analysis

Contrary to expectations, results from the PCA of Procrustes superimposed data suggest that the two samples in this study are similar. Most of the variance in the shape of the PCA samples is accounted for by the first ten principal components (~95%) (Table 2.2). Scatter plots of the first three principal components with convex hulls show that there is general overlap between the two samples (Fig. 2.5). However, the observed overlap in PCA scatter plots may be a result of a small number of specimens that represent shape outliers.

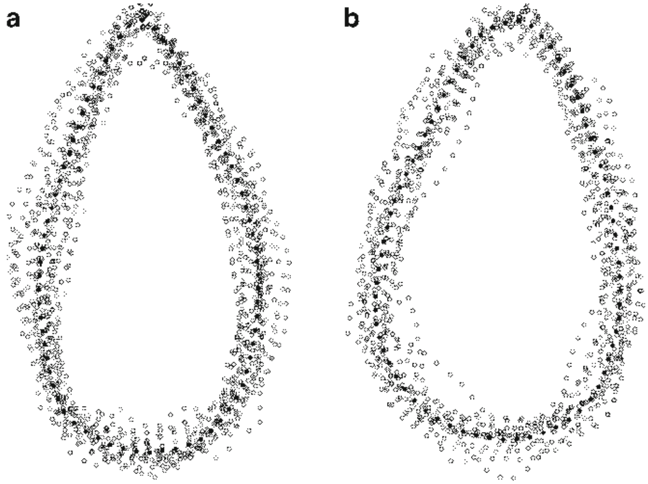

Fig. 2.4 Side-by-side Procrustes dimensionless juxtaposition of (**a**) bone and (**b**) stone bifaces from Castle di Guido. Mean biface shapes in *bold*, empty points are individual specimens

Table 2.2 Percentage shape variance explained by each principal component from the analysis

PC	Eigenvalue	% Variance	Cumulative % variance
1	0.130594	44.445	44.445
2	0.0487438	16.589	61.034
3	0.027677	9.4192	70.4532
4	0.0237399	8.0793	78.5325
5	0.0153975	5.2402	83.7727
6	0.0133478	4.5426	88.3153
7	0.00767623	2.6124	90.9277
8	0.0041865	1.4248	92.3525
9	0.0035769	1.2173	93.5698
10	0.00337478	1.1485	94.7183
11	0.00287224	0.9775	95.6958
12	0.00227543	0.77439	96.47019
13	0.00155896	0.53056	97.00075
14	0.00141924	0.48301	97.48376
15	0.00124356	0.42322	97.90698
16	0.000889937	0.30287	98.20985
17	0.000737633	0.25104	98.46089
18	0.000588693	0.20035	98.66124
19	0.00054509	0.18551	98.84675
20	0.000477487	0.1625	99.00925

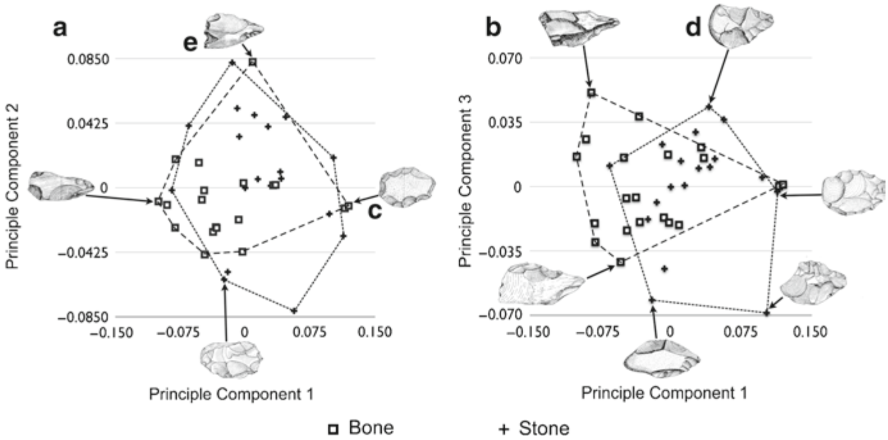

Fig. 2.5 (**a**) Scatter plot of principal components one and two with convex hulls, (**b**) scatter plot of principal components one and three with convex hulls, (**c**) a very ovate bone biface at the far right of principal component one, (**d**) intermediate stone ovate biface with a cortical butt and moderate reduction shows how incidental factors may have influenced shape, (**e**) the shape of this triangular bone biface may have also been influenced by incidental factors such as skeletal element morphology

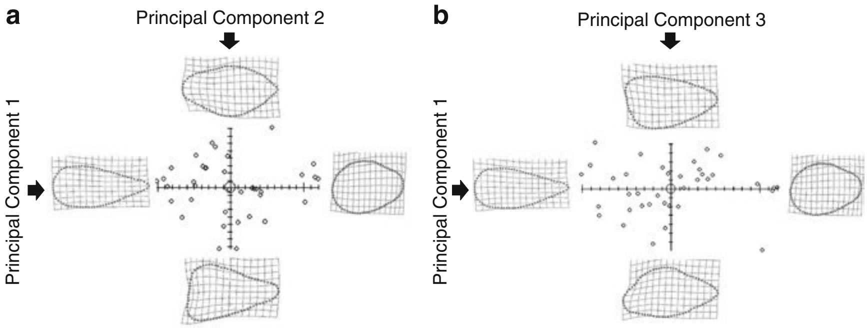

Fig. 2.6 Principal component scatter plots and deformed grids (thin-plate splines) illustrating shape deformation or changes along each principal component axis relative to the mean shape. (**a**) Principal component one and two. (**b**) Principal component one and three

By examining the thin-plate spline deformations along the relative warp axes (i.e., principal components axes) in the program tpsRelw and *XY* plots of specimens from the PCA scatters, it was possible to interpret the shape variation which each principal component encompassed (Fig. 2.6). Principal component one, illustrated by the horizontal axis of both illustrations in Figs. 2.5 and 2.6, represents elongation or “pointedness” vs. “ovateness” of the bifaces. Principal component two is the position of maximum breadth along the longitudinal length of the bifaces. Principal component three is more ambiguous; however, it appears to be related to the

position of maximum breadth relative to the base (i.e., base "pointedness") and perhaps to asymmetry as well.

Looking at principal component one in the plots illustrated in Fig. 2.5, we see that the bone sample is generally more pointed than the stone sample (i.e., most points are to the left of the plot). Yet, two of the bone bifaces represent some of the most ovate-shaped tools in the study (Fig. 2.5c). Many of the ovate stone specimens, which plotted on the far right axis of principal component one, had unflaked cortical butts and were generally only moderately worked (Fig. 2.5d). The latter stone shapes contrast with the more ovate bone specimens in that the bone group is more intensively worked and nearly discoidal in plan form (see Fig. 2.5c). Considering the apparent degree of reduction, the highly ovate shape of the bone biface group along principal component one can be attributed to anthropogenic agents. In comparison, the form of the stone biface group along principal component one may be constrained by natural factors (i.e., core morphology) and/or other human-mediated causes such as a limited degree of reduction. On the opposite end of principal component one's axis (i.e., the left side of Fig. 2.5a, b), the most pointed bone specimens are generally only partially flaked (~75% circumference), whereas the few pointed stone specimens have heavily reduced (biconcave) tips.

Looking at principal component two (Fig. 2.5a), one finds that the position of maximum breadth overlaps in both groups. This result is consistent with prior observations that biface morphology often exhibits less variability in width relative to length (McPherron 2006). The bone group, however, has a much more consistent distribution in the placement of maximum breadth, with one exception (see Fig. 2.5e); this bone specimen is triangular in shape and its shape may reflect the fact that it appears to have been fashioned from the naturally triangular morphology of the anterior crest of a tibia (additional knowledge of the third dimension would throw light on this). Finally, scatter plots of principal component three (see Fig. 2.5b) show that the stone group has some pointed bases, whereas the bone group is intermediate in base morphology.

MANOVA/CVA

Two tests for MANOVA and CVA of the first 20 principal component scores and eigenscores of bone and stone samples indicated no significant difference between the two biface groups [PCscores $F=0.8635$, $p=0.6268$/Eigenscores $F=0.8483$, $p=0.6409$] (Fig. 2.7). These results were contrary to expectations, but in accordance with that observed from the high degree of overlap observed in PCA scatter plots and a qualitative evaluation of mean Procrustes superimposed shapes for each sample. Note that although the bone and stone samples examined here are not significantly different, they do separate slightly in the CVA scatter plot shown in Fig. 2.7. This disparity is interpreted as reflecting the elongation or "pointedness" relative to width differences represented by principal component one which explains up to 45% of the overall shape variance (see Table 2.2).

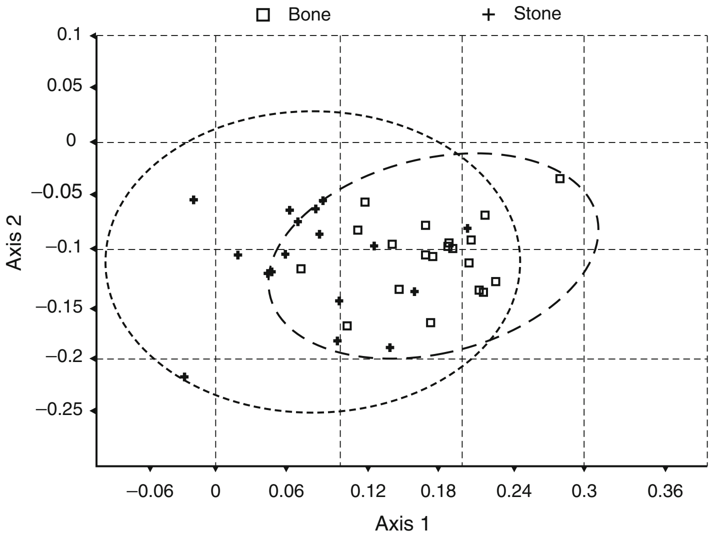

Fig. 2.7 Canonical variate analysis scatter plot of eigenscores with 95% confidence ellipses

Discussion

Evaluation of Methods

Some of the main differences in shape between the stone and bone bifaces detected in this study were variables that are captured by the length ratios and other measurements used in traditional biface shape analysis (i.e., elongation, location of maximum breadth) (e.g., Roe 1968). Therefore, if the material was available, a traditional metric analysis of these stone and bone tools would likely provide comparable 2D shape results as well as information on the omitted variable of thickness and shape of the third dimension in general. Nevertheless, the methodology applied here accounts for more idiosyncrasies in tool form and removes the influence of isometric size from the analysis, allowing allometric differences in biface form to be controlled (Crompton and Gowlett 1993; Gowlett and Crompton 1994; Lycett et al. 2006). However, this analysis was based on digitized biface images that have some important analytical limitations. An ideal morphometric analysis involves direct laboratory study of the artifacts. Accordingly, while the 2D results of this work are in some ways more instructive than a traditional metric analysis of biface shape, this study does not account for 3D variation in biface thickness and other idiosyncratic attributes that may constitute some difference not presently observed between the two groups.

Evaluation of Materials

It is possible that sample bias may have influenced the results of this study. The analyzed materials were not ideal in all respects. The Castel di Guido bifaces were selected for this study because they are assumed to be relatively synchronous and are much more closely associated relative to any other available data of this type. The biface shape data were limited to only those specimens illustrated in the Castel di Guido monograph (Radmilli and Boschian 1996). Ninety-nine flaked bone bifaces have been reported from Castel di Guido, but only 20 of these could be studied (Radmilli and Boschian 1996). Furthermore, it is probably safe to assume that those bone bifaces judged as best (i.e., specimens most convincingly modified by hominins and those which fit the typological models that archaeologists have for stone bifaces) were preferentially selected for illustration. This sampling bias could have influenced the results of this study.

The integrity of the stone sample was most likely affected in a similar way to the bone sample. The lithic assemblage from Castel di Guido was relatively deficient in stone bifaces ($n = 74$) and thus the stone sample for this study was slightly smaller than the bone sample. In addition to a dissimilar relative abundance of specimens, the stone biface sample from Castel di Guido was somewhat irregular (i.e., less well-made), so it is possible that the stone biface sample used in this study is not representative of the true population of shape variation for Acheulean bifaces 300,000 years BP. Under these circumstances, collecting additional outline data from bifaces of definite temporal similarity and from within the immediate area (i.e., Latium Province) to ensure a more representative stone sample seems plausible. However, that step was beyond the present study and again it would be preferable to collect further data firsthand rather than through photographs of illustrations. Nevertheless, the results of this study indicate that, at least in some cases, knapping procedures more routinely seen in stone bifaces were applied in the manufacture of bone bifaces with sufficient fidelity that differences between samples are statistically nonsignificant.

General Considerations: Natural Vs. Artificial Forces in Biface Plan Shape

This analysis made the assumption that intraclass differences in raw material type (e.g., *Elephas antiquus* vs. *Bos primigenius*, bone/chert vs. quartzite) and their potential influence on biface shape are minor relative to interclass differences (e.g., bone vs. stone). However, bone is a complex material and analogies to stone technology can be useful, but also perilous. Unlike most isotropic crypto-crystalline lithic materials utilized by Paleolithic knappers, bone is anisotropic, breaking preferentially in a longitudinal direction in long bones (Johnson 1985). Additional variables unique to using bone as a flaking material, such as cortical bone thickness, time of acquisition

and environment (i.e., bone weathering), percussor type used, bone element morphology, mineralogical content, animal nutrition, will all influence the final shape of an artifact. Likewise stone has its own unique variables that influence tool morphology (Ashton and White 2003; Clark 1980; Jones 1979). The high degree of roundness observed on principal component one for several bifaces made on river cobbles that had unmodified butts illustrates this problem (see Fig. 2.5d). Yet the influence of natural core shape may also be related to the intensity of reduction.

McPherron (1994, 1999, 2003, 2006) has observed that size and reduction intensity are crucial factors affecting biface shape. In this study, a contrast in shape ("pointedness" vs. "ovateness") between the two biface groups can be observed on principal component one, which may be related to reduction intensity (see Fig. 2.5). Each raw material type appears to converge in shape from an unmodified blank/core state along with the degree of reduction. At present, this relationship cannot be fully evaluated because size was removed from the analysis and no independent measure of reduction intensity was made. Nonetheless, if McPherron is correct, it may be that most of the shape variation found among the Castle di Guido bifaces can be attributed to reduction intensity (PC1 = 45%). A firsthand study of the Castle di Guido bifaces considering size and reduction intensity is needed to verify this observation.

It is difficult to judge for certain whether the Castel di Guido bifaces represent finished artifacts. Accounting for the degree of reduction and the possibility of recycling or resharpening is an important challenge for any analysis concerned with flaked artifact morphology and typology (Dibble 1988; McPherron 1994, 2006). However, it seems unlikely that the toolmakers of Castel di Guido could have inadvertently caused the statistical convergence of shape in the two materials accidentally through use or resharpening activities.

Many archaeologists have recognized the need to identify and exclude natural controls in order to make valid inferences on the anthropogenic controls governing Acheulean biface form (Ambrose 2001; Isaac 1986; Jones 1979; McPherron 2000). This study assessed whether natural or artificial forces were more important in determining the 2D shape of Acheulean bifaces. Two samples of extremely different materials were compared and in spite of expectations, the null hypothesis that the shapes of these artifacts were the same could not be rejected. These results may be interpreted as support for the argument that in some cases the plan shape of Acheulean bifaces is influenced more by anthropogenic (i.e., cultural) forces than natural ones (e.g., Wynn and Tierson 1990; Lycett and Gowlett 2008). Furthermore, it may be inferred from these results that the Acheulean toolmakers at Castel di Guido applied similar techniques in the production of both stone and bone bifaces (Villa and d'Errico 2001). This is not unexpected given that most Early Paleolithic evidence for flaked bone is found at Acheulean sites or in temporal contexts coeval with the latter (see Table 2.1).

Despite the results of this analysis, additional work is necessary to verify these observations and their interpretations. More robust comparative studies of flaked bone and stone artifacts are needed which specifically apply 3D approaches (e.g., Lycett et al. 2006) to larger more representative samples. These objectives

could be accomplished with an ideal sampling situation where the artifact raw materials are homogenous and well known. Experimental replicative studies of bone biface manufacture can illuminate natural variables that might affect artifact morphology (Backwell and d'Errico 2005; Stanford et al. 1981). Although the unflaked experimental bone specimen included in the study appears somewhat biface-like in shape (see Backwell and d'Errico 2005: 261), the results of the PCA shows that it can be distinguished in plan form from the true bone and stone bifaces from Castel di Guido (see Fig. 2.5). Even so, additional experiments and morphological analyses of flaked large mammalian bone are necessary to further support this observation.

Conclusions

A geometric morphometric analysis of plan shape from digitized images of stone and bone biface artifacts was undertaken to quantitatively evaluate 2D morphological similarity. The results indicate that the null hypothesis that there is no difference in the 2D shape of each artifact material class cannot be rejected. This result may be interpreted as evidence that 2D shape concepts of Acheulean stone bifaces were directly applied in the production of bone bifaces.

Therefore, this work quantitatively validates what is apparent from illustrations of these bone bifaces, namely, that they are congruent in plan shape to Acheulean stone bifaces. Additional studies concerning bone technology and geometric morphometric analyses, particularly those incorporating the third dimension will offer more insight and perhaps alternative explanations for the 2D morphological correspondence seen in the Castle di Guido bifaces. Ultimately, further analyses with this methodology may test the strength of these conclusions by examining the controls in 2D biface form using distinct lithic raw materials from the same archaeological context.

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References

Ambrose, S., 2001. Paleolithic technology and human evolution. *Science* 291: 1748–1753.

Anzidei, A.P., 2001. Tools from elephant bones at La Polledrara di Cecanibbio and Rebibbia-Casal de' Pazzi. In *The World of Elephants*, edited by G. Cavarretta, P. Gioia, M. Mussi, and M.R. Palombo, pp. 415–418. Consiglio Nazionale delle Ricerche, Rome.

Ashton, N. and White, M., 2003. Biface and raw materials: flexible flaking in the British Early Paleolithic. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H. Dibble, pp. 109–125. University of Pennsylvania, Philadelphia.

Backwell, L.R. and d'Errico, F., 2004. Additional evidence on early hominid bone tools from Swartkrans. In *Swartkrans: A Cave's Chronicle of Early Man,* Second ed., edited by C.K. Brain, pp. 279–295. CTP Book Printers, Capetown.

Backwell, L.R. and d'Errico, F., 2005. The origin of bone tool technology and the indentification of early hominid cultural traditions. In *From Tools to Symbols: From Early Hominids to Modern Humans*, edited by F. d'Errico and L.R. Backwell, pp. 238–275. Witswatersrand University Press, Johannesburg.

Backwell, L.R. and d'Errico, F., 2008. Early hominid bone tools from Drimolen, South Africa. *Journal of Archaeological Science* 35(11): 2880–2894.

Bailey, R.C. and Byrnes, J., 1990. A new, old method for assessing measurement error in both univariate and multivariate morphometric studies. *Systematic Zoology* 39(2): 124–130.

Biberson, P., 1961. *Le Paleolithique Inferieur du Maroc Atlantique*. Publications du Service d'Antiquite du Maroc, Memoire.

Bidditu, I. and Cassoli, P.F., 1969. Una stazione del Paleolitico Inferiore a Pontecorvo in Provincia di Frosinone. *Quarternaria* 10: 167–197.

Bidditu, I., Cassoli, P.F., di Brozolo, F.R., Segre, A., Naldini, E.S. and Villa I., 1979. Anagni, a K-Ar dated Lower and Middle Pleistocene site, central Italy: preliminary report. *Quaternaria* 21: 53–70.

Bidditu, I. and Celletti, P., 2001. Plio-Pleistocene proboscidea and Lower Palaeolithic bone industry of southern Latium (Italy). In *The World of Elephants*, edited by G. Cavarretta, P. Gioia, M. Mussi and M.R. Palombo, pp. 91–96. Consiglio Nazionale delle Ricerche, Roma.

Bidditu, I. and Segre, A., 1982. *Utillizzazione dell'osso nel Paleolitico Inferiore Italiano, Firenze*, edited by M. Piperno, pp. 89–105. Instituto Italiano di Prehistoria e Protostoria, Roma.

Blumenshine, R.J. and Pobiner B.L., 2006. Zooarchaeology and the ecology of Oldowan hominin carnivory. In *Evolution of the Human Diet*, edited by P.S. Ungar, pp. 167–190. Oxford University Press, Oxford.

Brain, C.K. and Shipman, P., 1993. The Swartkrans bone tools. In *Swartkrans: A Cave's Chronicle of Early Man*, edited by C.K. Brain, pp. 195–215. Transvaal Museum, Pretoria.

Brande, S. and Saragusti, I., 1999. Graphic visualization of handaxes and other artifacts. *Near Eastern Archaeology* 62(4): 242–245.

Buchanan, B., 2006. An analysis of Folsom projectile point resharpening using quantitative comparisons of form and allometry. *Journal of Archaeological Science* 33(2): 185–199.

Callow, P., 1976. *The Lower and Middle Palaeolithic of Britian and Adjacent Areas of Europe* [unpublished PhD Thesis]. University of Cambridge, Cambridge.

Cassoli, P.F., DeGiuli, C., Radmilli, A.M. and Segre, A.G., 1982. Giacimento del Paleolitico Inferiore a Malagrotta (Roma). *Atti della XXIII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria* 23: 531–549.

Clark, J.D., 1977. Bone tools of the earlier Pleistocene. *Eretz Israel* 13: 23–37.

Clark, J.D., 1980. Raw material and African lithic technology. *Man and Environment* 4: 44–55.

Clark J.D., 1994. The Acheulean Industrial Complex in Africa and elsewhere. In *Integrative Paths to the Past*, edited by R.S. Corruccini and R.L. Ciochon, pp. 451–469. Prentice-Hall, New Jersey.

Crompton, R.H. and Gowlett, J.A.J., 1993. Allometry and multidimensional form in Acheulean bifaces from Kilombe, Kenya. *Journal of Human Evolution* 25: 175–199.

Dibble, H., 1988. Typological aspects of reduction and intensity of utilization on lithic resources in the French Mousterian. In *Upper Pleistocene Prehistory of Western Eurasia*, edited by H. Dibble and A. Montet-White, pp. 181–197. University of Pennsylvania Museum, Philadelphia.

Dobosi V.T., 2001. Ex proboscideis- Proboscidean remains as raw material at four Palaeolithic sites, Hungary. In *The World of Elephants*, edited by G. Cavarretta, P. Gioia, M. Mussi and M.R. Palombo, pp. 429431. Consiglio Nazionale delle Ricerche, Roma.

Domínguez-Rodrigo, M. and Egeland, C.P. (Eds.), 2007. *Deconstructing Olduvai: A Taphonomic Study of the Bed I Sites*. Springer Verlag, Berlin.

Geraads, D., Hublin, J., Jaeger, J., Tong, H., Sen, S. and Toubeau, P., 1986. The Pleistocene hominid site of Ternifine, Algeria: New results on the environment, age, and human industries. *Quaternary Research* 25: 380–386.

Gowlett, J.A.J., 2006. The elements of design form in Acheulian bifaces: modes, modalities, rules and language. In *Axe Age: Acheulian Tool-Making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 203–222. Equinox, London.

Gowlett, J.A.J. and Crompton, R.H., 1994. Kariandusi: Acheulean morphology and the question of allometry. *African Archaeological Review* 12: 3–42.

Günther, B. (Ed.), 1988. *Alt- und mittelsteinzeitliche Fundplätze in Westfalen Münster Westfalen*. Westfälisches Museum für Archäologie.

Hammer, Ø. and Harper, D.A.T., 2006. *Paleontological Data Analysis*. Blackwell Publishing, Malden.

Hammer, Ø., Harper, D.A.T. and Ryan, P.D., 2001. PAST: Paleontological statistics package for education and data analysis. *Palaeontologia Electronica* 4(1): 9.

Heinzelin, de J., Clark, J.D., White, T., Hart, W., Renne, P., WoldeGabriel, G., Beyene, Y. and Vrba, E., 1999. Environment and behavior of 2.5-Million-Year-Old Bouri Hominids. *Science* 284: 625–629.

Henshilwood, C.S. and Sealy, J.C., 1997. Bone artefacts from the Middle Stone Age at Blombos Cave, Southern Cape, South Africa. *Current Anthropology* 38(5): 890–895.

Isaac, G.L., 1977. *Olorgesailie: Archaeological Studies of a Middle Pleistocene Lake Basin in Kenya*. University of Chicago Press, Chicago.

Isaac, G.L., 1986. Foundation stones: Early artefacts as indicators of activities and abilities. In *Stone Age Prehistory: Studies in Memory of Charles McBurney*, edited by G. Bailey and P. Callow, pp. 221–241. Cambridge University Press, Cambridge.

Johnson, E., 1985. Current developments in bone technology. *Advances in Archaeological Method and Theory* 8: 157–235.

Jones, P.R., 1979. Effects of raw materials on biface manufacture. *Science* 204: 835–836.

Leakey, M.D., 1971. *Olduvai Gorge: Excavations in Beds I and II, 1960–1963, Volume 3*. Cambridge University Press, Cambridge.

Lemorini, C., 2001. Seeing use-wear on the "oldest tools": La Polledrara di Cecanibbio and Casal de'Pazzi (Rome). In *The World of Elephants*, edited by G. Cavarretta, P. Gioia, M. Mussi and M.R. Palombo, pp. 57–58. Consiglio Nazionale delle Ricerche, Roma.

Lycett, S.J., 2007. Is the Soanian Techno-Complex a Mode 1 or Mode 3 phenomenon? A morphometric assessment. *Journal of Archaeological Science* 34(9): 1434–1440.

Lycett, S.J. and Gowlett, J.A.J., 2008. On questions surrounding the Acheulean 'tradition'. *World Archaeology* 40: 295–315.

Lycett, S.J., von Cramon-Taubadel, N., and Foley, R.A., 2006. A Crossbeam Co-ordinate Caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33: 847–861.

MacLeod, N., 1999. Generalizing and extending the eigenshape method of shape space visualization and analysis. *Paleobiology* 25(1): 107–138.

Mallegni, F., Mariani-Costantini, R., Fornaciari, G., Longo, E.T., Giacobini, G., and Radmilli, A.M., 1983. New European fossil hominid material from an Acheulean site near Rome (Castel di Guido). *American Journal of Physical Anthropology* 62(3): 263–274.

Mallegni, F. and Radmilli, A.M., 1988. Human temporal bone from the Lower Paleolithic site of Castel di Guido, near Rome, Italy. *American Journal of Physical Anthropology* 76(2): 175–182.

Mania, D., 1987. Homo erectus from Bilzingsleben (GDR): His culture and his environment. *L'Anthropologie* 11: 3–45.

McPherron, S.P., 1994. *A Reduction Model for Variability in Acheulean Biface Morphology* [unpublished PhD thesis]. University of Pennsylvania, Philadelphia.

McPherron, S.P., 1999. Ovate and pointed handaxe assemblages: two points make a line. *Préhistoire Européenne* 14: 9–32.

McPherron, S.P., 2000. Handaxes as a measure of the mental capabilities of early hominids. *Journal of Archaeological Science* 27: 655–663.

McPherron, S.P., 2003. Technological and typological variability in the bifaces from Tabun Cave, Israel. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H. Dibble, pp. 55–75. University of Pennsylvania, Philadelphia.

McPherron, S.P., 2006. What typology can tell us about Acheulian handaxe production. In *Axe Age: Acheulian Tool-making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 267–285. Equinox, London.

McPherron, S.P. and Dibble, H.L., 1999. Stone tool analysis using digitized images: examples from the Lower and Middle Paleolithic. *Lithic Technology* 24(1): 38–52.

Patou-Mathis, M., 1999. Les outils du Paleolithique Inferieur et Moyen en Europe. In *Prehistoire d'Os. Aix-en-Provence*, edited by H. Camps-Fabier, pp. 49–57. Univeriste de Provence, Marseille.

Radmilli, A.M. and Boschian, G., 1996. *Gli Scavi a Castel di Guido: Il piu Antico Giacimento di Cacciatori del Paleolitico Inferiore nell'Agro Romano*. Instituto Italiano di Preistoria e Protostoria, Florence.

Roe, D., 1964. The British Lower Palaeolithic: some problems, methods of study and preliminary results. *Proceedings of the Prehistoric Society* 30(13): 245–267.

Roe, D., 1968. British Lower and Middle Palaeolithic handaxe groups. *Proceedings of the Prehistoric Society* 34(1): 1–82.

Rohlf, F.J., 2004. *tpsDig*. Version 1.40. SUNY, Stony Brook.

Rohlf, F.J., 2006a. *tps Utility Program*. Version 1.38. SUNY, Stony Brook.

Rohlf, F.J., 2006b. *tpsRelw*. Version 1.44. SUNY, Stony Brook.

Scott, K., 1980. Two hunting episodes of Middle Paleolithic age at La Cotte de Saint-Brelade, Jersey (Channel Islands). *World Archaeology* 12: 137–152.

Scott, K., 1986a. The bone assemblages of layers 3 and 6. *La Cotte de St. Brelade, Jersey Excavations by C. B. M. McBurney 1961–1978*, edited by C.B.M. McBurney and P. Callow, pp. 159–183. Geo Books, Norwich.

Scott, K., 1986b. The large mammal fauna. *La Cotte de St. Brelade, Jersey Excavations by C. B. M. McBurney 1961–1978*, edited by C.B.M. McBurney and P. Callow, pp. 59–183. Geo Books, Norwich.

Scott, K., 1989. Mammoth bone modified by humans: Evidence from La Cotte de St. Brelade, Jersey, Channel Islands. In *Bone Modification*, edited by R. Bonnichsen and M.H. Sorg, pp. 335–346. Center for the Study of the First Americans, Orono.

Segre, A. and Ascenzi, A., 1984. Fontana Ranuccio: Italy's earliest Middle Pleistocene hominid site. *Current Anthropology* 25(2): 230–233.

Shipman, P., 1989. Altered bones from Olduvai Gorge, Tanzania: techniques, problems and applications of their recognition. In *Bone Modification*, edited by R. Bonnichsen and M.H. Sorg, pp. 317–334.Center for the Study of the First Americans, Orono.

Singer, R. and Wymer, J., 1982. *The Middle Stone Age at Klasies River Mouth in South Africa.* University of Chicago Press, Chicago.

Stanford, D., Bonnichsen, R., and Morlan, R.E., 1981. The ginsberg experiment: modern and prehistoric evidence of a bone-flaking technology. *Science* 212: 438–440.

Stekelis, M., 1967. Un lissoir en os du Pleistocene Moyen de la Vallee du Jourdain. *Revista da Faculdade de Letras de Lisboa* 3(10): 3–5.

Straus, L.G., 1995. The Upper Paleolithic of Europe: an overview. *Evolutionary Anthropology* 4(1): 4–16.

Toth, N. and Schick, K., 1993. Early stone industries and inferences regarding language and cognition. In *Tools, Language and Cognition in Human Evolution*, edited by K. Gibson and T. Ingold, pp. 346–362. Cambridge University Press, Cambridge.

Villa, P., Anzidei, A.P. and Cerilli, E., 1999. Bone and bone modifications at La Polledrara: A Middle Pleistocene site in Italy. In *The Role of Early Humans in the Accumulation of European Lower and Middle Palaeolithic Bone Assemblages*, edited by S. Gaudzinski and E. Turner, pp. 197–206. Romisch-Germanisches Zentralmuseum in Verbindung mit der European Science Foundation, Mainz.

Villa, P. and d'Errico, F., 2001. Bone and ivory points in the Lower and Middle Paleolithic of Europe. *Journal of Human Evolution* 41: 69–112.

Vincent, A., 1993. *L'Outillage Osseux au Paleolithique Moyen: Une Nouvelle Approache* [un published PhD thesis]. Universite de Paris, Paris.

Wynn, T., 1995. Handaxe enigmas. *World Archaeology* 27: 10–24.

Wynn, T. and Tierson, F., 1990. Regional comparison of the shapes of later Acheulean handaxes. *American Anthropologist* 92: 73–84.

Yellen, J.E., Brooks, A.S., Cornelissen, E., Mehlam, M. and Stewart, K., 1995. A Middle Stone Age worked bone industry from Katanda, Upper Semliki Valley, Zaire. *Science* 268: 553–556.

Chapter 3
Regional Diversity Within the Core Technology of the Howiesons Poort Techno-Complex

Chris Clarkson

Abstract This chapter works from the assumption that core technology is a culturally transmitted practice that is more conducive to tracking cultural phylogenies than retouched implements that have undergone strong selection and convergence for functional properties. This chapter presents an analysis of core traditions within the MSA of southern Africa using multivariate morphometric analysis of cores from five Howiesons Poort sites. Results suggest that regional traditions of core reduction existed within this widespread techno-complex despite strong similarities in backed artefact technologies. This raises the possibility that backed artefact manufacturing technology spread between local populations that had inherited quite different approaches to core reduction.

Introduction

Archaeology has long seen documenting the rise of human diversity as one of its primary descriptive and explanatory goals. No region on earth is of greater importance in understanding the origins of human diversity than sub-Saharan Africa. Africa is the likely birthplace of modern humanity and the origin point from which a small subset of that diversity sprung forth to colonize the rest of the world. By 100,000 years ago, it is clear that a diverse group of modern human populations was present in Africa, and that at least one of these groups had temporarily colonized neighbouring regions. The widespread use of composite technologies (Brooks et al. 2006; Lombard 2008; Wadley et al. 2004), symbolism, and sophisticated technological and economic practices (e.g. marine exploitation, increased diet breadth, exotic raw material procurement and exchange, heat treatment, hunting with projectiles, possible use of nets, etc.) also appear in Africa along with regionally distinctive lithic technologies such as the Aterian, Still Bay, and Howiesons Poort (HP), at this time (Barham 2001; Bouzouggara

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et al. 2008; Clark 1988; Clark and Plug 2008; Cremaschi et al. 1998; d'Errico et al. 2003, 2005; Henshilwood et al. 2001; Henshilwood and Marean 2003; Marean et al. 2007; Marwick 2003; McBrearty and Brooks 2000; Volman 1978; Wendorf and Schild 1974). This story of the birth and spread of cultural and biological modernity is unfolding at an ever quickening rate, with multiple lines of evidence strengthening interpretations and generating new and more interesting questions.

Stone artefacts clearly have an enormous role to play in the unfolding story of modern human origins. Indeed, there is little alternative but to engage this body of evidence in order to fill the enormous gaps that exist in the skeletal and genetic record of modern human evolution, a gap that will likely never be filled by this kind of evidence alone. Archaeologists should therefore benefit from developing methods that can accurately describe technological similarity and difference on the same terms for any assemblage, as well as develop the necessary theoretical underpinnings required to understand the mechanisms that create diversity or homogeneity in lithic industries in relatively settled populations, make comparisons between the technologies of different regions (Brooks et al. 2006; Petraglia et al. 2007) and better understand the technological changes that take place at the wave front of human dispersals.

No current analytical system is able to adequately capture variation in the full range of lithic technologies (i.e. bifacial, blade, radial or multiplatform reduction technologies, etc.) across vast regions so that diversity and rates of change in technological features (e.g. shape, flaking pattern, platform preparation, etc.) can be measured. The focus here is placed on the analysis and comparison of core technology for reasons discussed in detail below. This approach has the potential to offer a different though perhaps complementary view of regional diversity within the Africa Middle Stone Age to that presented by McBrearty and Brooks (2000) and Brooks et al. (2006) for points.

This chapter attempts preliminary characterization of technological diversity through comparison of the HP levels of five sites located in South Africa, dating to between 64.8 and 59.5 kya (Jacobs et al. 2008). The purpose of this case study is to illustrate the potential of this approach to detect regional variation within technological traditions that appear homogeneous on the basis of their retouched component. Regional variability is not a feature currently remarked upon for the HP and the image presented is one of a common technological tradition of synchronous origin and comparable duration present across much of South Africa (Jacobs et al. 2008), although temporal changes and various technological differences have of course been noted within the HP (Mackay and Welz 2008; Soriano et al. 2007). The case study presented here detects marked variability within core technology for this techno-complex for the first time, raising questions about the meaning of pronounced diversity within a widespread tradition, and the means by which that diversity arose within a comparatively short time span.

Why Cores?

Cores, or the remnant nuclei left from flake production, provide an appropriate focus for understanding the advent of human technological diversity and for tracking the technologies of dispersing human groups. This is because they are rarely used or modified after flake production ends, and therefore retain much information

about culturally transmitted procedures of stone artefact manufacture employed throughout the reduction sequence.

Cores also form a manageable subset of the often enormous quantities of stone artefacts found in archaeological sites. They also preserve information about reduction intensity, which can obscure previous stages of reduction, but also inform about the organization of technology and economic pressures and constraints.

Finally, core technology is ubiquitous among all stone using populations of this period, whereas regionally distinctive retouched artefacts are not always present in lithic assemblages. Furthermore, the diversity and morphology of retouched implements have more reason to be responsive to functional and organizational demands (such as mobility frequency and magnitude, time stress, and risk) than do the techniques of blank production (within certain limits) (Binford 1970; Shott 1986; Kuhn 2005; Torrence 1989; Clarkson 2007). Retouched implements are also more likely to comprise the visible components of technology in the sense that they were likely maintained, transported, exchanged, and discarded over longer time spans, allowing greater opportunities for horizontal transmission of artefact designs, uses, and hafting arrangements. Final retouched artefact forms are also easier to replicate through individual experimentation than the multiple steps and stages of core reduction (along with its distinctive debitage). Various steps and stages of manufacture employed to make a particular artefact, attempts to replicate the final artefact form will likely incorporate errors and deviations that mean the cores and debitage differ somewhat from the original assemblage (Flenniken 1981; Hiscock 1988). This is seen for instance in the numerous ways modern flintknappers have arrived at replicating. Mesoamerican pressure blade cores. Anyone who has watched a skilled knapper reduce a core using techniques with which they are unfamiliar, and without a running commentary, will know that this can be a bewildering blur of movements, core rotations, and preparatory actions that are unconducive to accurate replication without close study and numerous repetitions. Variation in core technology should therefore provide the best means of detecting lines of cultural transmission as might be implicated in the appearance of distinctive regional traditions. Core technology should therefore provide an enormously valuable source of information about the appearance and degree of cultural diversity among early modern humans.

A New Approach to Quantifying Variation in Core Technology

While sophisticated new analyses are appearing for a range of lithic artefact types (as represented by the chapters in this volume), core technology has remained poorly explored in technological terms, and many incompatible typologies and poorly defined technological concepts dominate this field of study. The system presented here attempts to build a holistic measure of core form and technology by incorporating three-dimensional analysis of flake scar patterning with more conventional analyses of shape and core attributes to build a multidimensional description of core technology (Fig. 3.1).

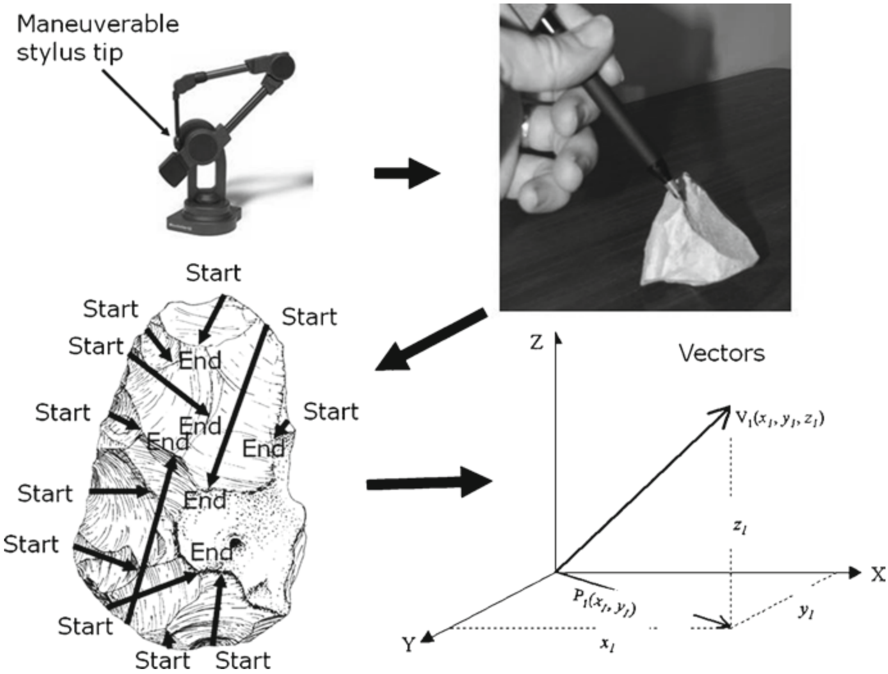

Fig. 3.1 Use of a Microscribe to capture 3D coordinates with which to calculate vectors for each flake scar

The first component of this method, generating an index of scar patterning using 3D scar analysis, is described in detail in Clarkson et al. (2006). A Microscribe (*Immersion Corporation*), or pivoting digitiser, is used to record flake scar patterns on cores in three dimensions. To generate an index of flake scar pattering, *X*, *Y*, *Z* coordinates are taken for the start and end points of each scar on a core for upper and lower hemispheres, determined by the arrangement of surfaces and platforms. The start and end points for each scar are then converted into vectors describing size and direction of each scar. The vectors for all the scars found on each side of a core are then averaged to provide a description of the degree to which scars travel in the same direction, that is, how parallel they are to one another, or the degree to which their different orientations cancel each other and are thus randomly orientated. Flake scar patterns that are centripetal will tend to fall part way between these two extremes. These differences in scar patterning can be expressed as a single angle measure ranging between 0° and 90°, with 0 representing truly parallel flake scar alignments and 90 representing truly random (i.e. non-aligned) flake scar orientations. This index represents the average angle between any two flake scars picked at random on the core face.

This approach was tested on 30 experimental cores of extremely homogeneous black Suffolk flint. The cores were knapped by the author to generate different flake scar patterns and forms, including bifaces, Levallois and discoidal cores,

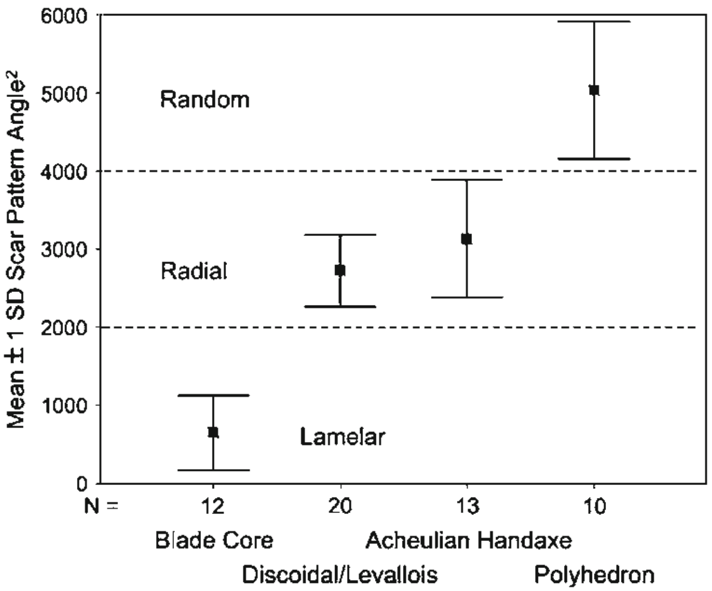

Fig. 3.2 Results of 3D scar pattern analysis for a range of core types

pressure and hard hammer blade cores, and polyhedrons that are heavily rotated and opportunistically flaked around their entire surfaces. The bifaces, discoidal and Levallois cores all exhibited centripetal flaking, the blade cores all had more or less parallel flake scar orientations, and the polyhedrons had more or less random flake scar orientations. Centripetal, parallel, and random flake scar patterns all separate from one another very well (Fig. 3.2), indicating that this technique provides an effective measure of scar patterning.

A holistic description of core technology must also incorporate measures of core shape. Axial measurements of core length, width and thickness were taken at orientations determined by core shape and scar pattern (Fig. 3.3). For cores that clearly have top and bottom surfaces (e.g. discoids, Levallois cores, bifaces, conical cores and unidirectionally flaked cylindrical cores), the length axis passes through the centre of the top and bottom surfaces. Otherwise, length is the longest axis of the core when the axis passes through the centre of its mass. Width and thickness are measured orthogonal to length at the centre point of the length axis. For Levallois cores, width A (proximal width) is taken from the centre of the platform used to strike the Levallois flake (the "front" of the core) to the opposite end of the core face. For bifaces and handaxes, width A is treated as the widest end of the length axis (usually the "butt end") and width B is taken at the opposite end of the width axis (usually the tip). Width is the next longest axis in this case, and thickness the next longest after width.

Angle measurements that describe the degree of expansion or contraction of a core along its two major axes of height and length were also used to measure core shape. The angle of contraction or expansion of the core is calculated from width

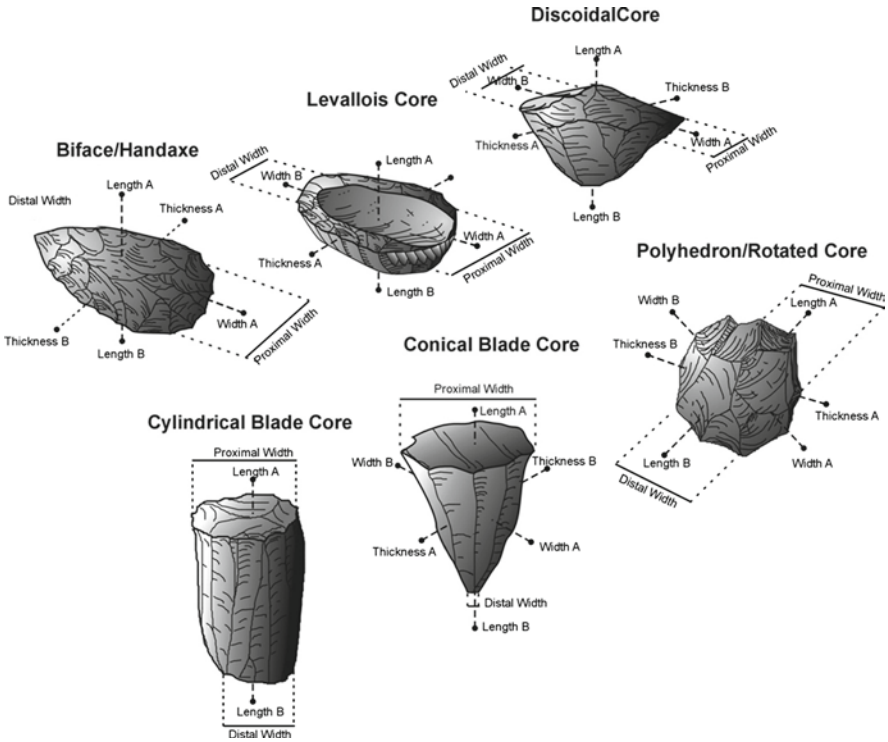

Fig. 3.3 Core types showing the orientation of axial measurements taken on cores of different shape, platform arrangement, and removal surfaces

measurements at both ends of the longest axis of the core, calculated using the following formula:

$$\tan\frac{\theta}{2} = \frac{((\text{Proximal width} - \text{Distal width})/2)}{\text{Length}}$$

$$\text{And hence angle of the lateral margins } (\theta) = 2\tan^{-1}\frac{\text{Proximal width} - \text{Distal width}}{2\times \text{Length}}.$$

where proximal width is the width of the widest end of the core, or the principal platform in the case of Levallois cores or the last used platform in the case of discoids, and distal end is the narrower end or the distal end of the core face when a platform exists at one end of the longest axis.

The degree of lateral and distal convexity on one or more of the core surfaces, and a measure of asymmetry in the intersection height of surfaces are also employed. The curvature of core face is measured following Boëda's (1995) concept of distal surface convexity. The measure is a ratio of the height of core face above the plain of intersection between top and bottom, or front and back, or worked and unworked surfaces of the core, and the length of the core face. Asymmetry in intersection height measures the point of intersection on the length axis (as a percentage of length from base) of

upper and lower faces for discoids, Levallois cores and bifaces, or of the main platform to core face along the length axis for all other core types, including conical cores, unidirectionally flaked cylindrical cores, multiplatform cores, etc. Perfect symmetry of upper and lower halves gives a result of 50%. Cores that have flat bases and steeply domed upper surfaces have low percentage values while cores with flat tops and keeled or domed bases have high percentage values.

The combination of these variables generates six measures of core shape used in the multivariate analysis: Length to width ratio, width to thickness ratio, core face curvature, the angle of expansion or contraction along the longest shape axis of the core, the mean angle of intersecting surfaces and/or platforms, and the point at which surfaces intersect (i.e. top and bottom surfaces, platforms, etc.) along the length axis of the core. Ratios and angles provide information on "shape" but do not adequately resolve issues of size differences between different cores. 3D geometric morphometric techniques of core analysis are now being adopted in place of ratios and angles (following Lycett et al. 2006); however, the data were not available for this analysis.

A third component of core analysis involves recording core attributes relevant to production technology, such as the number of platforms, the proportion of the platform edge that is facetted, the proportion of scars that are elongate (length > 2 × width) and parallel-sided, and the proportion of the core face over which the longest or preferential scar runs (longest scar/core face length) (Fig. 3.4).

Platform angles, proportions of cortex, number of scars, and proportions of step terminations are also recorded to examine the effects of reduction intensity on core morphology (Fig. 3.4).

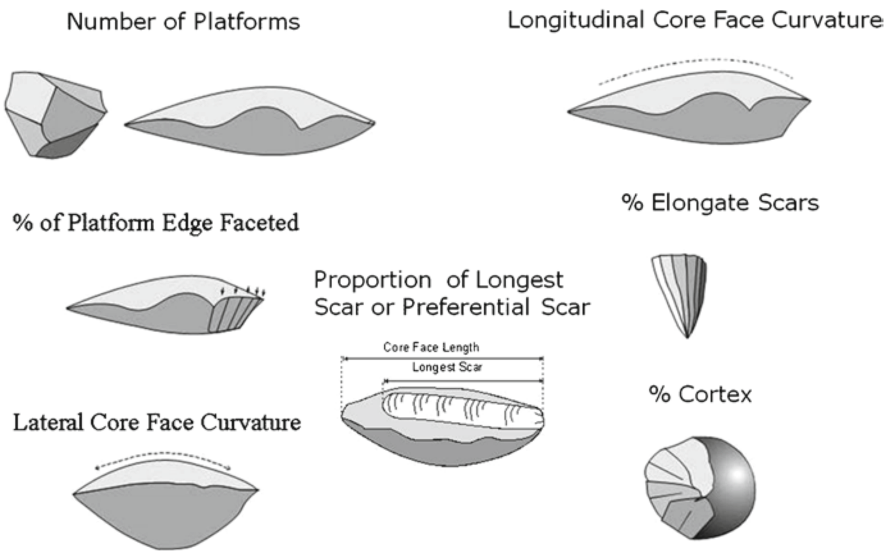

Fig. 3.4 Technological attributes recorded on each core

To remove kurtosis from some variables, a square root transformation was performed on the ratio of length to width, the ratio of width to thickness, and the measure of core face curvature. Proportional values were also transformed using the following formula: $\log(p/1-p)$ for use in the discriminant analysis.

Testing the Method

A first test of this approach to describing core technology involves determining how successfully it discriminates between core shapes. For this purpose, a discriminant analysis is performed on 780 cores from 30 African and Levantine Middle Stone Age and Middle Palaeolithic sites likely associated with modern humans, to see if cores of different shape classes would cluster together. The analysis of core shape indicates that the choice of variables separates core shapes into meaningful clusters very well (Fig. 3.4). Since the collections comprise archaeological cores that incorporate a degree of variation around the ideal form for each core shape, the results show the technique to be robust since different core types cluster together, albeit with some overlap, while the group centroids remain clearly distant from one another. The first and second discriminant functions explain as much as 88% of the variation in the sample of cores. Curvature of the core face, the ratio of length to width and width to thickness measurements and the intersection height between upper and lower surfaces have the largest absolute correlations with Function 1, whereas average edge angles, flake scar pattern angle, proportion of blade scars, and the proportion of the longest flake scar to core face length have the largest correlations with Function 2. All Functions (1–3) are significant at the $p = <0.0005$ level.

A second test of the method determines how well classic Palaeolithic core typologies are replicated by this technique (Fig. 3.5). For this test, 3D scar pattern, shape, and technological data are combined in a discriminant function analysis of 532 Middle Stone Age Cores representing classic core types from this period. It is interesting to note that the main area of overlap is between discoidal and Levallois cores, which are often noted to bear strong resemblance to one another technologically and typologically. Eigenvalues are 1.321 and 1.147 for Functions 1 and 2, and these two functions explain 87.9% of the total variance. Functions 1–10 are all significant at the $p=<0.0005$ level. The sample of cores are reclassified into their correct classes in 77–93% of cases, with Levallois Point and classic Levallois cores showing the most classificatory confusion with one another. This is not altogether surprising given the strong similarity in techniques, and the tendency for some Levallois cores to become discoidal at later stages of reduction (Fig. 3.6).

This technique is therefore capable of replicating traditional core categories in quantitative terms. It is also be able to detect similarities and differences within and between sites and regions. To provide a preliminary test of the ability to explore diversity in MSA core technology, a case study is presented from the HP in South Africa.

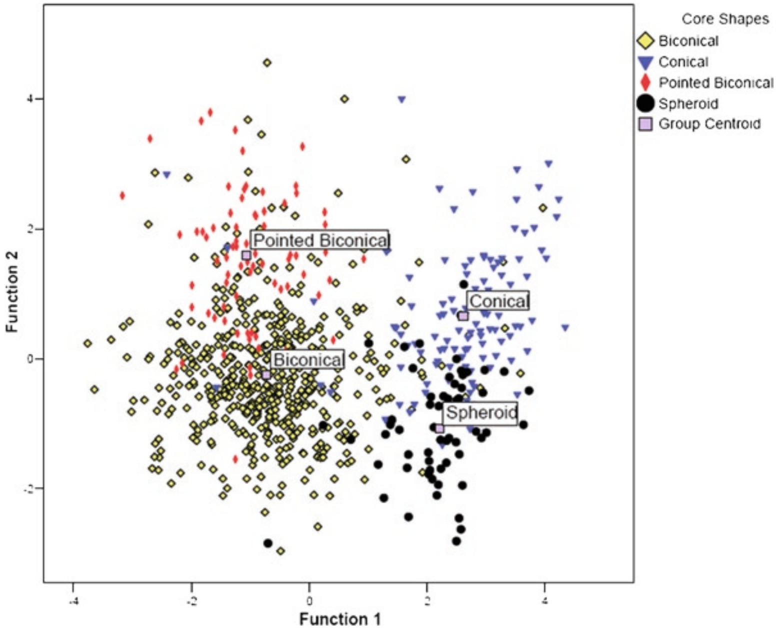

Fig. 3.5 Discriminant analysis of core shape using 778 Middle Stone Age African and Levantine Middle Palaeolithic Cores. Functions 1 and 2 together explain 88% of the total variance

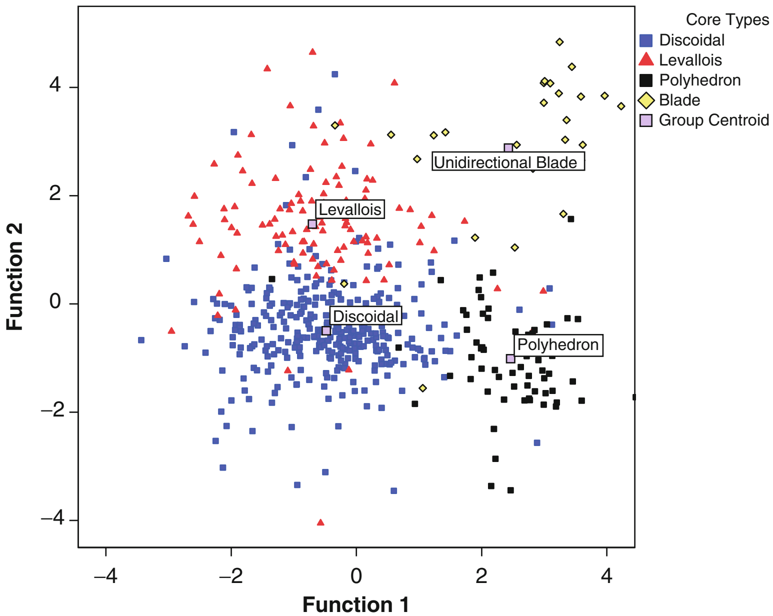

Fig. 3.6 Discriminant function analysis of 3D scar pattern, shape and technological data from 532 Middle Stone Age/Middle Palaeolithic Cores from Africa and the Levant representing classic core types from this period. Functions 1 and 2 together explain 88% of the total variance

Regional Variability Within the Core Technologies of the HP

The HP is noted for the appearance of backed flakes and blades, high proportions of exotic stone, and is unambiguously detected from the Western Cape of South Africa to northeastern South Africa. Recent dating of a large number of HP occurrences across South Africa suggests that this techno-complex dates between ca. 64.8 and 59.5 kya (Jacobs et al. 2008), and follows after the Still Bay industry, dated at ca. 71.9 and 71 kya. While the formal retouched implements from HP sites have received a lot of attention, core technology is poorly documented.

It is possible to examine whether the HP in fact exhibits internal variability by analyzing core technologies from five sites. These are located in the Western Cape (Diepkloof and Klein Kliphuis), Southern Cape (Klasies River Mouth and Nelson Bay Cave) and central eastern South Africa (Rose Cottage Cave) (Wurz 2002; Mackay 2006; Rigaud et al. 2006; Soriano et al. 2007; Volman 1978) using the same methods as above. As shown in Fig. 3.7, the Western Cape, Southern Cape, and Rose Cottage Cave cores all form discrete groupings with little overlap. Cores classify back into their region in 72.8% of cases, whereas cores correctly classify back into raw material type in only 46% of cases. Raw material differences are pronounced between regions, however, suggesting that material type and regional differences are difficult to disentangle without further exploration of the data.

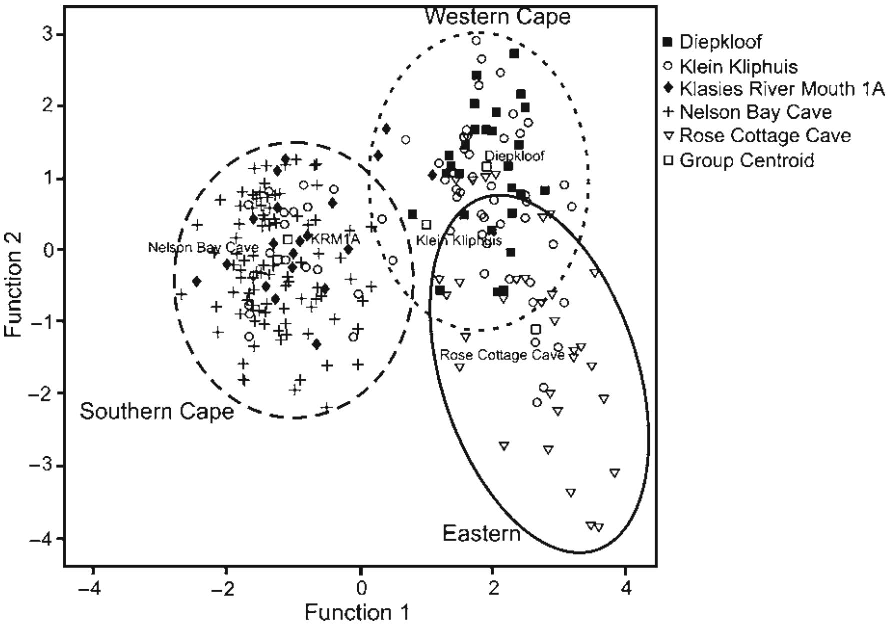

Fig. 3.7 Discriminant function analysis of five sites from the South African Howiesons Poort techno-complex, showing pronounced regional variability in core technology

Nevertheless, raw material differences would appear to be subservient to other causes of variation in creating differences between regions.

These regional clusters naturally raise the question of what might be driving apart these blank production systems, given the common use of high quality raw material, a common technological product in the form of small flakes, blades, and backed artefacts, and a comparatively short time span for this technological phase.

We can further explore what is driving some of these differences by plotting the first and second discriminant function scores against several key technological variables. In Fig. 3.8a, Function 1 is plotted against the number of scars found on cores in each region. Figure 3.8b plots Function 1 against a transformed index of the percentage of blade scars (see above) found on cores by region. Figure 3.8c shows the index of scar patterning plotted against Function 2, and Fig. 3.8d shows

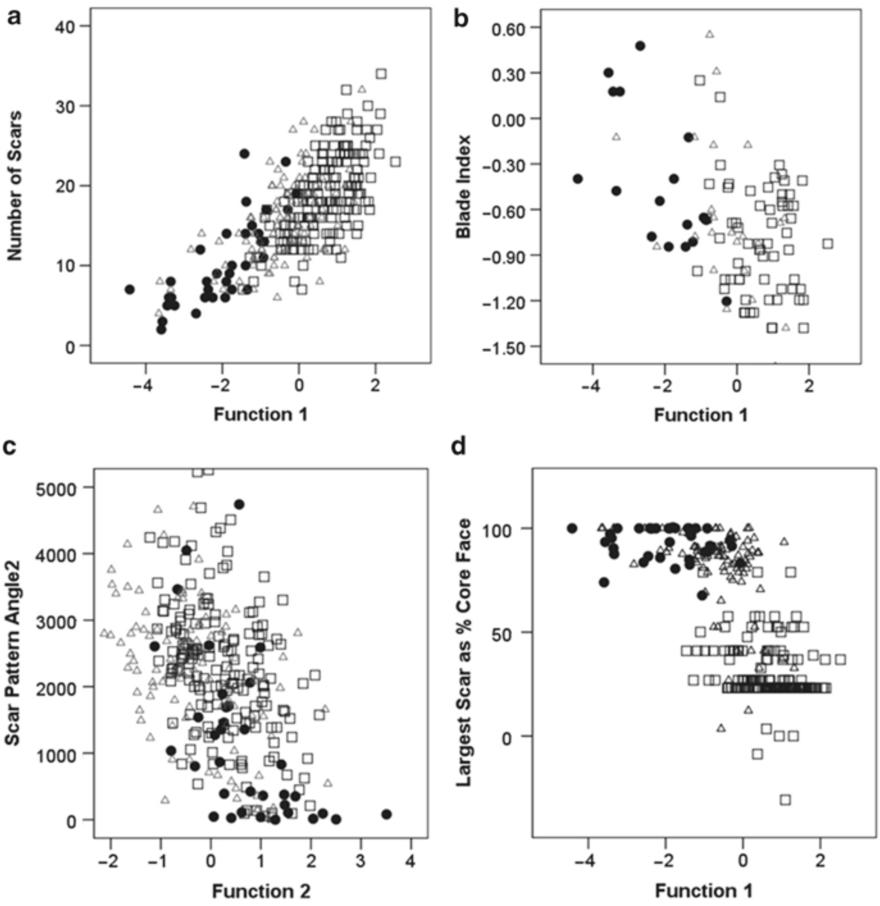

Fig. 3.8 Key technological variables plotted against function scores. *Black circles*: Rose Cottage Cave; *hollow squares*: Southern Cape (Klasies River and Nelson Bay Cave); *hollow triangles*: Western Cape (Diepkloof and Klein Klphuis)

Function 1 plotted against the proportion of the core face over which the largest or preferential scar (in the case of Levallois) runs. The solid black dots represent Rose Cottage Cave (the easternmost HP site in the sample), the hollow squares are Southern Cape sites, and the hollow triangles are Western Cape sites.

This set of graphs makes apparent a number of the important differences between core assemblages. Rose Cottage Cave assemblages are clustered at one end for all of these scatter plots, indicating these cores have fewer scars, are much more focused on blade production than other HP sites, possess core face scar patterns indicative of more parallel scar arrangements, and show at least one large scar running virtually the entire length of the core face. Core technologies of the Western and Southern Cape tend to be more radial in scar pattern arrangement, with more flake scars and fewer elongate flake removals. These differences are consistent with more discoidal and Levallois-like reduction on the Western and Southern Cape and more blade-like core reduction at Rose Cottage Cave. Figure 3.8d highlights an important distinction between the Southern and Western Cape cores. Final or largest flake scars on the Southern Cape cores tend to run only midway along the core face, whereas Western Cape cores have longest or preferential scars that tend to run closer to the full length of the core. The Western and Southern cape cores also show significant (t-test, $p = <0.0005$) differences in the distal curvature (or doming) of the upper core surface, with Western Cape cores showing much flatter core faces. These combinations of characteristics suggest that cores of the Western Cape better fit the description of Levallois, whereas those from the Southern Cape better fit the discoidal category. This observation from the data certainly fits the impressions of the author while measuring the material. Illustrations of the cores (in preparation) will also help illustrate these differences in future.

Discussion

What implication does regional variation in core reduction and blank production have for understanding the organization of technology in the HP? These results seem to suggest that backing could be and was performed on a wider range of flake blank forms than is commonly perceived, as the kinds of flakes removed from these cores probably differed in a number of ways, such as elongation, parallelness of the margins, platform and dorsal scar morphology. Flakes produced at Rose Cottage Cave should be more likely to exhibit parallel dorsal ridges and parallel or tapering margins and plain or crushed platforms typical of blade production, while flakes from the Cape would be more likely to show less parallel-margins, more complex dorsal scar patterns and platform morphologies typical of discoidal or Levallois production. Comparison of the flakes used to make backed artefacts at Diepkloof on the Western Cape, which were made on larger and more irregular flakes (Mackay 2008), and those from Rose Cottage Cave, which were typically made on small, very regular blades (Soriano et al. 2007), offer some preliminary support for this observation.

Recent experiments have found insignificant differences in the cutting edge to mass ratios produced for radial and blade cores, both for the individual flakes and over the entire reduction history of the cores (Eren et al. 2008; and confirmed by the author's own experiments). This suggests that significantly different cutting edge to mass ratios (i.e. raw material efficiency) should not distinguish modes of flake production in any region, but result from different approaches to flake removals from cores, such as striking closer to the edge to remove thinner flakes for a given surface area. Mackay (2006, p. 620) finds, for example, that increased cutting edge length to mass (EL/*M*) efficiency in flakes manufactured during the HP at Diepkloof do "not correlate with any changes in dominant implement type, and thus blank form and EL/*M* values are capable of operating as independent variables."

The fact that very different technologies can produce flakes with similar properties in terms of cutting edge/mass and functional propensities, and that raw materials from all sites are of high quality, suggests there was no inherent reason for knappers to chose one technology over another, allowing quite different core reduction strategies to emerge and co-exist within the same techno-complex for the simple reason that both produced acceptable flake blanks for no loss in efficiency. The explanation for what drove the emergence of distinctive flake technology in the HP then should reside in understanding the circumstances that required the use of backed flakes, rather than certain core technologies. Changes in hunting techniques and the demand for greater effectiveness in capturing large prey may have a great deal to do with the appearance and spread of backed technologies (and such changes may have superimposed more conservative, localized approaches to blank production). This hypothesis is more consistent with the multiple independent origins of backed technologies in different times across the globe (Bleed 2002; Clarkson et al. 2009; Elston and Brantingham 2002; Hiscock and O'Connor 2005; Lombard and Pargeter 2008) than the diffusion of a single cultural package (Mellars 2006). Further testing and exploration of these arguments requires detailed analysis of flake assemblages beyond the scope of this chapter, particularly since cores are recovered at the point of discard, and hence earlier stages of reduction may be better examined on flakes than cores. The system of core reduction is nevertheless apparent on discarded cores despite the absence of information about earlier stages of reduction.

The point being made here reiterates the arguments advanced at the beginning of this chapter. This is that core technology could well have the potential to tell us about quite different cultural processes than does the retouched component of an industry. The retouched component which will be more susceptible to convergence and horizontal transmission than the more elaborate and less easily observed and imitated procedures of core reduction. Many different core technologies were clearly available and even co-existed within the African MSA at various times (Petraglia et al. 2007). What core technology people adopted and passed on in various places might tell us more about cultural transmission processes over varying time scales, and hence the formation and maintenance of cultural lineages (O'Brien et al. 2008), than it does about the functional demands of the technology. Function is probably a story better told by the retouched tools that were designed, shaped, curated, recycled and displayed by the past human groups to meet specific purposes than the lumps of rock from which they derived.

It is not yet possible to rule out raw material variation as a cause of much of the assemblage variability seen in the core technologies of the HP; however, it may also be the case that regional diversity points to more ancient cultural lineages in place in these regions prior to the spread of point and backed artefact technologies as solutions to the problems of the time. Despite some arguments to the contrary (Jacobs et al. 2008), we cannot overlook the fact that both the Still Bay and the HP fall within a period of significant overall worsening of climatic conditions during OIS4, providing a parsimonious explanation for the move towards standardized, highly retouched and curated implements for use in composite technologies at this time. Surprisingly, change in this component of the technology towards standardized toolkits would appear not to have generated the same degree of standardization in core technologies. Looking for antecedent technologies (e.g. Tostevin 2003) in earlier times in each region (such as the Still Bay) may be the next step to detecting long-term, regional cultural traditions in flake production that were resilient to the effects of changing retouched implement design.

Conclusion

The analytical system presented here serves as a first attempt to describe in holistic terms the nature of the lithic technologies found in early modern human sites in the southern African HP, a period that is highly significant for immediately preceding the modern human colonization of the rest of the world (Jacobs et al. 2008; Mellars 2005). The technique presented here provides a relatively fast and powerful alternative to typology and more unidimensional analyses of core form that allows similarity and difference to be quantified in various ways. Discriminant analysis is only one technique for exploring this data, and many univariate and multivariate techniques will lend extra explanatory and descriptive power to such analyses. Its ability to classify new assemblages into the map of technological variation for Africa and surrounding regions will also offer the potential to describe assemblages in common terms while simultaneously identifying the discriminating technological characteristics that differentiate those technologies.

To better characterize the phylogeny of core technologies at regional scales, assuming this is what is partly driving observed differences, we must turn to cladistics. Recent case studies demonstrate the potential for cladistic analysis to test phylogenetic hypotheses, and this approach offers great potential for future analysis of African MSA assemblages, since the modern human lineages that were appearing and colonizing new regions at this time might be expected to have left distinctive technological traces (Lycett 2007; Buchannan and Collard 2008; O'Brien et al. 2008). The approach presented here will not only serve as a source of hypotheses for such analyses, but should also help determine the kinds of characters required to successfully undertake cladistic analysis of core assemblages during this important period in human evolution.

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References

Barham, L.S., 2001. Backed tools in the Middle Pleistocene central Africa and their evolutionary significance. *Journal of Human Evolution* 43: 585–603.

Binford, 1970. Re-tooling: towards a behavioral theory of stone tools. *Time, Energy and Stone Tools*. R. Torrence. Cambridge, University of Cambridge: 57–66.

Bleed, P., 2002. Cheap, regular and reliable: implications of design variation in late Pleistocene Japanese microblade technology. In *Thinking Small: Global Perspectives on Microlithization* edited by R.G. Elston and S.L. Kuhn, pp. 95–102. Archaeological Papers of the American Anthropological Association, Arlington.

Boëda, E., 1995. Levallois: a volumetric construction, methods, a technique. In *The Definition and Interpretation of Levallois Technology* edited by H. Dibble and O. Bar-Yosef, pp. 41–69. Monographs in World Prehistory, No. 23. Prehistory Press, Madison, WI.

Bouzouggara, A., Bartonb, N., Vanhaerend, M., d'Errico, F., Collcutth, S., Highami, T., Hodge, E., Parfittk, S., Rhodes, E., Schwenninger, J-L., Stringer, C., Turner, E., Wardo, S., Moutmirp, A. and Stamboulip, A., 2008. 82,000-Year-old shell beads from North Africa and implications for the origins of modern human behaviour. *Proceedings of the National Academy of Science USA* 104: 9964–9969.

Brooks, A.S., Nevell, L., Yellen, J.E. and Hartman, G., 2006. Projectile technologies of the African MSA: implications for modern human origins. In *Transitions Before the Transition: Evolution and Stability in the Middle Paleolithic and Middle Stone Age* edited by E. Hovers and S.L. Kuhn, pp. 233–255. Springer, New York.

Buchannan, B. and Collard, M., 2008. Testing models of early Paleoindian colonization and adaptation using cladistics. In *Cultural Transmission and Archaeology: Issues and Case Studies* edited by M.J. O'Brien, pp. 59–76. Society for American Archaeology, Washington, DC

Clark, J.D., 1988. The middle stone age of East Africa and the beginnings of regional identity. *Journal of World Prehistory* 2: 235–305.

Clarkson, C., 2007. *Lithics in the Land of the Lightning Brothers*. Canberra, ANU E Press.

Clark, J.L. and Plug, I., 2008. Animal exploitation strategies during the South African Middle Stone Age: Howiesons Poort and pos-Howiesons Poort fauna from Sibudu Cave. *Journal of Human Evolution* 54: 886–898.

Clarkson, C., Vinicius, L. and Lahr, M.M., 2006. Quantifying flake scar patterning on cores using 3D recording techniques. *Journal of Archaeological Science* 33(1): 132–142.

Clarkson, C., Petraglia, M., Korisettar, R., Haslam, M., Boivin, N., Crowther, A., Ditchfield, P., Fuller, D., Miracle, P., Harris, C. and Connell, K., 2009. The oldest and longest enduring microlithic sequence in India: 35,000 years of modern human occupation and change at the Jwalapuram Locality 9 rockshelter. *Antiquity* 83(2): 326–348.

Cremaschi, M., Di Lernia, S. and Garcea, E.A.A., 1998. Some insights on the Aterian in the Libyan Sahara: chronology, environment, and archaeology. *African Archaeological Review* 15: 261–286.

d'Errico, F., Henshilwood, C. and Lawson, G., 2003. Archaeological evidence for the emergence of language, symbolism, and music – an alternative multidisciplinary perspective. *Journal of World Prehistory* 17: 1–70.

d'Errico, F., Henshilwood, C.S., Vanhaeren, M. and van Niekerk, K., 2005. *Nassarius kraussianus* shell beads from Blombos Cave: evidence for symbolic behaviour in the Middle Stone Age. *Journal of Human Evolution* 48(1): 3–24.

Elston, R.G. and Brantingham, P.J., 2002. Microlithic technology in Northern Asia: a risk-minimizing strategy of the late Paleolithic and early Holocene. In *Thinking Small: Global Perspectives on Microlithization* edited by R.G. Elston and S.L. Kuhn, pp. 103–116. Archaeological Papers of the American Anthropological Association, Arlington.

Eren, M.I., Greenspan, A. and Sampson, G.C., 2008. Are Upper Paleolithic blade cores more productive than Middle Paleolithic discoidal cores? A replication experiment. *Journal of Human Evolution* 55(6): 952–961.

Flenniken, J.J., 1981. *Replicative Systems Analysis: A Model Applied to the Vein Quartz Artefacts from the Hoko River Site*. Pullman, Washington State University Laboratory of Anthropology.

Hudjashov, G., Kivisild, T., Underhill, P.A., Endicott, P., Sanchez, J.J., Lin, A.A., Shen, P., Oefner, P., Renfrew, C., Villems, R., Forster, P., 2007. Revealing the prehistoric settlement of Australia by Y chromosome and mtDNA analysis. *Proceedings of the National Academy of Science USA* 104(21): 8726–8730.

Henshilwood, C.S., Sealy, J.C., Yates, R., Cruz-Uribe, K., Goldberg, P., Grine, F.E., Klein, R.G., Poggenpoel, C., van Niekerk, K., Watts, I., 2001. Blombos Cave, Southern Cape, South Africa: Preliminary report on the 1992–1999 Excavations of the Middle Stone Age levels. *Journal of Archaeological Science* 28:421–448.

Henshilwood, C.S. and Marean, C.W., 2003. The origin of modern human behaviour: critique of the models and their test implications. *Current Anthropology* 44: 627–665.

Hiscock, P., 1988. *Prehistoric Settlement Patterns and Artefact Manufacture at Lawn Hill, Northwest Queensland*. Department of Anthropology and Sociology. Brisbane, University of Queensland.

Hiscock, P. and O'Connor, S., 2005. Arid paradises or dangerous landscapes. A review of explanations for Paleolithic assemblage change in arid Australia and Africa. In *Desert Peoples: Archaeological Perspectives* edited by P. Veth, M. Smith and P. Hiscock, pp. 58–77. Blackwell, Oxford.

Jacobs, Z., Roberts, R.G., Galbraith, R.F., Deacon, H.J., Grün, R., Mackay, A., Mitchell, P., Vogelsang, R. and Wadley, L., 2008. Ages for the Middle Stone Age of Southern Africa: implications for human behaviour and dispersals. *Science* 322: 733–735.

Kuhn, 2005. Re-tooling: towards a behavioral theory of stone tools. *Time, Energy and Stone Tools*. R. Torrence. Cambridge, University of Cambridge: 57–66.

Lombard, M., 2008. Finding resolution for the Howiesons Poort through the microscope: micro-residue analysis of segments from Sibudu Cave, South Africa. *Journal of Archaeological Science* 35(1): 26–41.

Lombard, M. and Pargeter, J., 2008. Hunting with Howiesons Poort segments: pilot experimental study and the functional interpretation of archaeological tools. *Journal of Archaeological Science* 35: 2523–2531.

Lycett, S.J., von Cramon-Taubadel, N. and Foley, R.A., 2006. A crossbeam co-ordinate caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33(6): 847–861.

Lycett, S.J., 2007. Why is there a lack of Mode 3 Levallois technologies in East Asia? A phylogenetic test of the Movius-Schick hypothesis. *Journal of Anthropological Archaeology* 26(4): 541–575.

Mackay, A., 2008. A method for estimating edge length from flake dimensions: use and implications for technological change in the southern African MSA. *Journal of Archaeological Science* 35(3): 614–622.

Mackay, A. and Welz, A., 2008. Engraved ochre from a Middle Stone Age context at Klein Kliphuis in the Western Cape of South Africa. *Journal of Archaeological Science* 35(6): 1521–1532.

Mackay, A., 2006. A characterization of the MSA stone artefact assemblage from the 1984 excavations at Klein Kliphuis, Western Cape. *South African Archaeological Bulletin* 61(184): 181–188.

Marean, C.W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A.I.R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P.J., Thompson, E., Watts, I. and Hope Williams, W.M., 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature* 449: 905–909.

Marwick, B., 2003. Pleistocene exchange networks as evidence for the evolution of language. *Cambridge Archaeological Journal* 13(1): 67–81.

McBrearty, S. and Brooks, S.A., 2000. The revolution that wasn't: a new interpretation of the origin of modern human behaviour. *Journal of Human Evolution* 39: 453–563.

Mellars, P., 2006. Going east: new genetic and archaeological perspectives on the modern human colonization of Eurasia. *Science* 313: 796–800.

Mellars, P., 2005. The impossible coincidence: a single species model for the origins of modern human behaviour in Europe. *Evolutionary Anthropology* 14: 27–43.

O'Brien, M.J., Lyman, R.L., Collard, M., Holden, C.J., Gray, R.D. and Shennan, S., 2008. Transmission, phylogenetics, and the evolution of cultural diversity. In *Cultural Transmission and Archaeology: Issues and Case Studies* edited by M.J. O'Brien, pp. 39–58. Society for American Archaeology, Washington, DC.

Petraglia, M., Korisettar, R., Boivin, N., Clarkson, C., Ditchfield, P., Jones, S., Lahr, M.M., Oppenheimer, C., Pyle, D., Roberts, R., Schwenninger, J.-L., Arnold, L. and White, K., 2007. Middle Palaeolithic assemblages from the Indian sub-continent before and after the Toba super-eruption. *Science* 317: 114–116.

Rigaud, J.-P., Texier, P.-J., Parkington, J. and Poggenpoel, C., 2006. Le mobilier Stillbay et Howiesons poort de l'abri Diepkloof. La chronologie du Middle Stone age sud-arficain et ses implications. *Palevol* 5: 839–849.

Shott, M. J., 1986. Technological organization and settlement mobility: An ethnographic examination. *Journal of Anthropological Research* 42:15–51.

Soriano, S., Villa, P. and Wadley, L., 2007. Blade technology and tool forms in the Middle Stone Age of South Africa: the Howiesons Poort and post-Howiesons Poort at Rose Cottage Cave. *Journal of Archaeological Science* 34: 681–703.

Torrence, R., 1989. Re-tooling: towards a behavioral theory of stone tools. *Time, Energy and Stone Tools*. R. Torrence. Cambridge, University of Cambridge: 57–66.

Tostevin, G., 2003. A quest for antecedents: a comparison of the terminal Middle Paleolithic and the early upper Paleolithic of the Levant. In *More than Meets the Eye* edited by N. Goring-Morris and A. Belfer-Cohen, pp. 54–67. Oxbow Books, Oxford.

Volman, T.P., 1978. Early archaeological evidence for shellfish collecting. *Science* 201: 911–913.

Wendorf, F. and Schild, R., 1974. *A Middle Stone Age Sequence from the Central Rift Valley, Ethiopia*. Polska Akedemia Nauk Intytut Historii Kultury Materialnej, Warsaw.

Wadley, L., Williamson, B.S. and Lombard, M., 2004. Ochre in hafting in Middle Stone Age Southern Africa: a practical role. *Antiquity* 78: 661–675.

Wurz, S.G.D., 2002. Variability in the Middle Stone Age lithic sequence, 115,000–60,000 years ago at Klasies River, South Africa. *Journal of Archaeological Science* 29: 1001–1015.

Chapter 4
Questioning the Link Between Stone Tool Standardization and Behavioral Modernity

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Abstract For more than 20 years, it has been claimed that standardization is a feature of Upper Paleolithic retouched stone tools, as compared to Middle Paleolithic ones, and reflects the stricter application of mental templates to stone tool-making (e.g., Mellars, Curr Anthropol 30:349–385, 1989a). More recently, this claim has been modified to include stone tool standardization as a feature of modern human behavior (e.g., Klein, J World Prehistory 9:167–198, 1995). It has been argued elsewhere (Chase 1991, Monnier, Cambridge Archaeological Journal 17:341–350, 2007) that standardization and apparent imposition of form in retouched tools reflect factors other than adherence to mental templates. This study tests the notion that standardization is a feature of behavioral modernity by comparing artifact standardization among Middle Paleolithic, Upper Paleolithic, and Neolithic assemblages from western Switzerland. It uses a 2D geometric morphometric approach to quantify variance in shape within selected tool types. The results show that the most highly standardized types occur in the Upper Paleolithic assemblage. Neolithic types are significantly less standardized than Upper Paleolithic types, and are *not* more standardized than Middle Paleolithic ones. This suggests that degree of standardization does not correlate strongly with behavioral modernity; rather, the occurrence of highly standardized tools in many Upper Paleolithic assemblages is a feature unique to the Upper Paleolithic, and the reasons for it most likely do not directly reflect mental templates or any other cognitive factors.

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Introduction

In recent years, there has been much discussion concerning the criteria upon which a definition of modern human behavior should be based (e.g., Klein 1995, 2000, 2008; McBrearty and Brooks 2000; Henshilwood and Marean 2003; d'Errico 2003). The technological criteria used in these definitions often include blade production and standardization of retouched stone tools. A frequently cited example of evidence in support of standardization as an indicator of modern behavior is the Howiesons Poort (HP) type backed tools of the Upper Paleolithic (UP), such as those occurring at the Klasies River main site in South Africa (Wurz 1999). Although the precocious nature of the Howiesons Poort industry was noted ever since its initial discovery, it was Deacon (1989) who stressed the standardization of the backed tools, suggesting they may have been used as symbols to cope with stress during deteriorating environmental conditions. More recently, a study by Wurz (1999) has provided quantitative support for the claim that HP tools are standardized. This study has been widely cited (McBrearty and Brooks 2000; Barham 2002; Henshilwood and Marean 2003; McBrearty 2007; Mellars 2007) in discussions of the apparent "modernity" of many aspects of the Middle Stone Age (MSA). Upon closer examination, however, it becomes apparent that the evidence for standardization provided in this study is somewhat scanty: Wurz looked at only one dimension of standardization, the coefficient of variation (CV) in the length of backed points. Another claim for standardization in the MSA is McBrearty's argument that "African MSA points show formal standardization and stylistic variation across space and time (McBrearty 2007, p. 136)." This claim, however, is primarily based on maps showing the geographic distribution of point styles (McBrearty and Brooks 2000; McBrearty 2007). Given the fact that all such claims for standardization in the African MSA are only weakly supported, this naturally raises the question as to why standardization is so often cited as a criterion of modern human behavior.

The concept of standardization as an indicator of modern behavior has historically been most strongly promoted by Mellars, who in 1989 published two articles which laid the basis for this claim. In the first (Mellars 1989a), he compared lithic technology across the Middle Paleolithic (MP)/Upper Paleolithic (UP) transition, identifying one of the changes in early UP stone tool forms as a higher degree of standardization and "a more obvious degree of 'imposed form' in the various stages of their production and shaping … [which] appear to reflect more clearly conceived 'mental templates' underlying their production" (Mellars 1989a, p. 365). In a separate article included in the proceedings of the Cambridge Human Revolution conference of 1987, he expanded the argument, concluding that increased standardization suggested a greater symbolic or cognitive component on the part of the tool makers (Mellars 1989b). For Mellars, then, who argued that the main feature of modern humans is the capacity for symbolic thinking, standardization of stone tools was one example of this ability. Similar arguments have been used by others. Wurz (1999) cites Byers' action-constitutive theory (Byers 1994) in her argument that standardization among the HP backed tools could be used as evidence of symbolling,

claiming that standardization indicates that behavior was guided by conventional social rules (Wurz 1999, p. 46). McBrearty attributes variation in form among MSA points to style, which she says indicates not only arbitrary, conventional dictates reflective of symbolic communication, but also the boundaries of linguistic or ethnographic groups (McBrearty 2007, p. 136). Regarding HP type tools, Henshilwood and Marean also state that "their imposed form and morphological standardization have clear symbolic significance" (Henshilwood and Marean 2003, p. 630).

This inclination to infer symbolic ability from standardization is challenged by a growing body of work which demonstrates that stone tool standardization and "imposed form" reflect factors other than cognitive ones (Chase 1991; Marks et al. 2001; Monnier 2006b, 2007; Nowell 2002). In some senses, this reflects the persistence of a traditional paradigm, similar to the one that associates blade technology with modern human behavior and that has now been debunked (Bar-Yosef and Kuhn 1999). The purpose of the present study was to contribute to this issue by testing the association between stone tool standardization and behavioral modernity.

The Historical Roots of the Standardization Argument

The paradigm that views increased standardization of stone tools as reflecting increased cognitive abilities has been persistent because it appeals to our intuitive sense that technology has progressed throughout the course of human history. It stems from the formative period of the field in the mid- to late-nineteenth century, when stone tools were seen as becoming increasingly finely worked and perfected through time. According to Trigger (1996), this view was a product of the Enlightenment ideals that pervaded scientific thought in Western Europe in the seventeenth century, lasting into the eighteenth and nineteenth centuries in some fields. These ideals posited that technological and cultural progress have been the main features of human development, and they meshed well with an account of human prehistory that confirmed this view (see Monnier 2006a, for a recent summary). It should therefore not be a surprise that some of our most cherished "facts" are rooted in these ideals. One of these "facts," or perhaps artifacts, is the notion that retouched stone tools become more standardized through time. De Mortillet, for example, stated that Acheulean handaxes became more finely and elegantly worked as they approached the Mousterian (de Mortillet 1883, p. 254). Two decades later, Commont used increasing refinement and perfection of handaxes as one of his criteria for defining phases of the Lower Paleolithic, such as pre-Chellean, Chellean, and Acheulean (Commont 1908). Similar statements can be found many decades later, in papers from a conference devoted to elucidating the Lower/Middle Paleolithic transition (Ronen 1982). It is clear from many of the contributors' comparisons of stone tools between the Lower and Middle Paleolithic that they viewed stone tools as evolving from rough precursors during the Lower Paleolithic to perfected forms by the end of the Middle Paleolithic (Monnier 2006b).

Mellars built on this concept, presenting it as a critical feature of the MP/UP transition (Mellars 1989a, b, 1991, 1996, pp. 133–136). He also linked standardization to the concept of the imposition of arbitrary form. This notion can be traced to Holloway's (1969) classic paper, which proposed that one of the most important elements of human culture is the imposition of arbitrary form upon the environment. Holloway argued that the act of transforming lithic raw material into stone tools is an example of imposition of arbitrary form because "there is no necessary relationship between the form of the final product and the original material" (Holloway 1969, p. 401). This led him to conclude that the shapes of stone tools are symbolic; he further suggested that stone tool-making and language are similar cognitive processes. Around the same time, James Deetz presented his notion of mental templates as "the idea of the proper form of an object [which] exists in the mind of the maker" (Deetz 1967, p. 34). Mellars used both the concept of the imposition of arbitrary form and the notion of mental templates to suggest that the makers of European Middle Paleolithic stone tools did not have the same cognitive abilities as the makers of early Upper Paleolithic stone tools, because the former artifacts were less standardized, exhibiting less imposed form and therefore more poorly defined mental templates.

Testing Standardization

Surprisingly, few studies have tested Mellars' claim that Upper Paleolithic stone tools are more standardized than Middle Paleolithic ones. One of the earliest is Chazan's comparison of measures of standardization and efficiency among Near Eastern and Western European Middle and Upper Paleolithic assemblages, which he used to test the hypothesis that the MP/UP transition was a result of the development of language (Chazan 1995). Chazan used several measures of standardization, one of which was a comparison of the distribution of tools in each assemblage according to metric attributes. He devised another measure of standardization which he called the "index of selection," in order to determine whether specific blanks were selected for retouch (selection of blanks of a specific size or shape would increase standardization among the tools made on these blanks). Unfortunately, this measure is flawed due to the fact that it does not take into account the fact that the original blank size and shape of the retouched pieces most likely changed as a result of retouch. Chazan concluded that there were no substantial differences in standardization between Upper and Middle Paleolithic assemblages. However, a number of commentators on the article found serious flaws with his analysis which, at the very least, call these conclusions into question (Belfer-Cohen 1995; Corbey and Roebroeks 1995; Graves-Brown 1995; Monnier 1995; van Peer 1995; Shea 1995).

In a study on the standardization of Howiesons Poort typed backed tools, Wurz (1999) used Chazan's "index of selection" to assess the size range of blanks that were chosen for the production of backed artifacts at Klasies River main site. She concluded that because more backed artifacts fall into smaller size classes than

"total blade blanks" (she did not specify whether this category includes retouched blades in addition to unretouched ones), smaller blanks were selected for the production of backed artifacts. In other words, she claims that the Klasies River hominins deliberately standardized the backed artifacts by selecting smaller blanks for their production. However, like Chazan's work, this approach ignores the real possibility that the size of the backed artifacts does not reflect the original size of the unretouched blank. Not only did blades likely lose some length as they were backed, but it is also possible that they were segmented, thereby losing a great deal of length. Wurz also tested the suggestion that backed artifacts are less standardized in the MSA than in the Later Stone Age (LSA). She used the CV of length to quantify standardization, and compared Howiesons Poort type backed artifacts from Klasies River main site, Nelson Bay Cave, and others with LSA "Wilton" backed artifacts. Finding that the CV of length is not appreciably greater in the LSA than in the MSA artifacts, she concluded that both types of artifacts "were designed with a comparable mental 'picture'" (Wurz 1999, p. 44). It is important to note, however, that she did not assess the variation for any metrical attribute other than length, such as width or laminarity. In sum, Wurz' data are an inadequate demonstration of standardization among HP backed tools.

In 2001, Marks and colleagues tested the "clarity of mental templates" between modern humans and Neanderthals by comparing burin standardization between Upper Paleolithic and Middle Paleolithic assemblages from the Near East and Western Europe (Marks et al. 2001). They used the CV of metric attributes which showed that the Upper Paleolithic burins are not more metrically standardized than the Mousterian burin sample. They also compared the diversity of burin types across assemblages, concluding that MP single burin types are not more diverse than the UP single burin types. In addition, they studied blank selection, the diversity of the shapes of retouched edges, and diversity in the position of the burin on the blank. None of these measures supported the idea that Upper Paleolithic burin assemblages are more standardized than Middle Paleolithic ones.

Finally, one of us (Monnier 2006b) investigated standardization among retouched stone tools in Middle Paleolithic assemblages from Western Europe. The purpose of that study was to test the notion that retouched tools become more standardized throughout the Middle Paleolithic. Using a variety of measures, including the CV of metric attributes, to quantify both standardization and the number and location of retouch types on each tool, no support for the notion that standardization increases through time in major tool classes of the three sites studied was found in that work.

Background to the Present Study

The previous discussion shows that several innovative measures have been developed to test for differences in standardization, either across the MP/UP or MSA/LSA transitions, or throughout the MP. There are two main problems with these studies, however.

The first is that none of the measures used to quantify standardization is a robust measure of shape. While length/width and width/thickness ratios provide simple shape statistics, they are only poor approximations of the actual shape of the tools. The second problem inherent in the studies that compared standardization across the MP/UP transition relates to the lack of comparability between Middle and Upper Paleolithic tool types. Middle Paleolithic assemblages tend to be dominated by scrapers and denticulates; Upper Paleolithic assemblages are dominated by end-scrapers, burins, and backed blades or bladelets. Marks et al. (2001) were able to solve this problem by finding a tool type common to both the UP and the MP sites in their study. However, in other cases, the problem of comparability between UP and MP contexts is often further exacerbated by blank shape differences. Many MP assemblages are dominated by flake-based technologies, whereas UP assemblages are dominated by blade technologies. In addition, there is the frequently mentioned issue that blades are more standardized in shape than flakes, which means that tools made from blades could appear more standardized than those made on flakes simply because blade blanks are more standardized to begin with. This leads to the circular, and unprovable, argument that blade technologies were used precisely because they produced standardized blanks.

In order to test the relationship between standardization and behavioral modernity, the present study sought to correct the methodological problems described above in two ways. First of all, geometric morphometric techniques were used to better represent shapes and shape differences of the tools. While this approach is most commonly used in the biological sciences, and especially in biological anthropology (see, e.g., Bookstein et al. 2004); Lycett and colleagues (Lycett et al. 2006; Lycett 2007; Lycett and von Cramon-Taubadel 2008) have successfully applied landmark morphometrics to lithic analyses. Geometric morphometric analysis is particularly well-suited to the study of stone tool standardization because it combines detailed models of tool shape with the rigorous methodologies of multivariate statistics. While previous standardization studies have only been able to compare one (e.g., length) or two (e.g., length:width ratio) variables at most, landmark studies can incorporate these traditional variables together with additional points that elucidate the artifactual shape between them. Finally, the mathematical transformations commonly used in geometric morphometrics remove isometric size differences between specimens. This is particularly important in standardization studies, where size and shape are easily confounded. While both factors undoubtedly play a role in standardization, it is crucial that they be addressed independently, so that the precise factors affecting standardization can be identified.

This study also sought to improve upon previous studies of standardization in MP and UP assemblages by adding two samples that are also associated with modern humans but from another time period. The Upper Paleolithic, it has often been pointed out, is not representative of the behavior of modern people everywhere, so our inclusion of Neolithic flaked stone assemblages from the same region provided a useful control. If stone tool standardization is a feature of modern human behavior, one would expect it to be greater in Neolithic as well as Upper Paleolithic assemblages than it is in Middle Paleolithic assemblages.

We tested the association between increased standardization and behaviorally modern humans by looking at the amount of variance present in different tool types from different modern human and Neanderthal localities. A strict interpretation of the "standardization hypothesis" would suggest that all tools associated with behaviorally modern humans conform to a more precise mental image than tools associated with more primitive human populations. A more relaxed interpretation might allow modern humans the *capacity* for greater standardization, whereby standardization is not uniformly sought, but might vary instead by tool types. Alternatively, if results show no difference in standardization, random differences, or standardization according to other factors (such as locality or raw material), this would support hypotheses that the degree of uniformity may reflect factors other than the mental capacity for generating preconceived templates.

Materials

In order to control for as many local factors as possible, the assemblages used in this study were chosen from a small region in western Switzerland and are all within 70 km of each other. This region encompasses the northern shore of Lake Neuchâtel and a nearby valley in the Jura Mountains. The Neolithic and Upper Paleolithic sites are located within 12 km of each other on the shore of the lake; the Middle Paleolithic site is 70 km to the North in a valley of the Jura.

Neuchâtel-Monruz

This site was discovered in 1989 during construction of the A5 autoroute along the northern and western shores of Lake Neuchâtel (Bullinger et al. 2006b). A salvage excavation was undertaken from 1989 to 1992, part of which entailed the removal of a 6×12-m block of the site for later excavation (Arnold 2006). The site contained both Azilian and Magdalenian occupations; the Magdalenian occupation was dated to 13,000 BP by C14 on charcoal taken from hearths. The Magdalenian level contained numerous hearths, well-preserved fauna, lithic and bone industries, ochre, and personal adornment items made from worked shell and jet. The lithic industry comprises more than 45,000 pieces larger than 1 cm; 1,354 of these are retouched tools, consisting of backed bladelets, burins, piercers, endscrapers, and pièces esquillées. Although 60% of the raw materials consist of a local, rather coarse-grained flint (Hauterive), the bulk of the retouched tools are made on much finer-grained flints imported from the Jura mountains to the north, between 80 and 150 km away. The retouched tools, analyzed by Bullinger et al. 2006a, are dominated by an abundance of backed bladelets, as well as burins and *perçoirs*. A random sample of complete (unbroken) backed bladelets and endscrapers was included in this study.

Auvernier-Port and Auvernier-la-Saunerie

The Auvernier sites are a series of Middle and Late Neolithic and Late Bronze Age villages located along a 1 km stretch of the northern shore of Lake Neuchâtel. The locality "La Saunerie" was discovered in the mid-nineteenth century and excavated by the Swiss archaeologist Paul Vouga from 1920 to 1930, who defined the Swiss lacustrine Neolithic on the basis of the stratigraphy of this site (Boiseaubert 1982). It was subsequently excavated by André Leroi-Gourhan and Samuel Perret from 1948 to 1950, by Christian Strahm from 1964 to 1965, and by Jean-Luc Boiseaubert from 1972 to 1975. The excavations during the 1960s and 1970s were carried out as part of a salvage project during the construction of the national highway RN 5. They revealed many other localities, such as Auvernier-Port, which has been dated to the Cortaillod period (approximately 3900–3400 BCE) of the Middle Neolithic. Dendrochronology of the pillars at Saunerie has revealed that the trees were cut between 2600 and 2434 BC, thereby dating the main component of the site to that period. The material culture from this site has been used to define a new facies, "Auvernier," of the Final Neolithic.

Although many publications on Auvernier-la-Saunerie exist, the lithic assemblage has not yet been published in its entirety. Much of Auvernier-Port also remains unpublished. The study of the material curated at the Laténium museum comprised 267 retouched artifacts from Auvernier-Port and 280 retouched artifacts from Auvernier-la-Saunerie, which were typed according to Honegger's (2001) typology of Middle and Final Neolithic retouched lithic artifacts. Because the raw materials used in prehistoric times in the region have been extensively studied (Affolter 2002), it was possible to identify some of the main differences between the two industries, such as differences in source material. At La Saunerie, almost 15% of the lithic component consists of large blades of Grand-Pressigny flint, imported from central France. These blades are often heavily retouched and reworked, and most often appear as retouched blades, knives, and endscrapers, although they sometimes have notches at the distal and proximal ends typical of laterally hafted knives or "saws" (like the bifacially worked *scie à encoches*). Other than the imported Grand-Pressigny materials, the inhabitants at La Saunerie made significant use of the local coarse-grained "Hauterive" chert. At Auvernier-Port, on the other hand, no Grand-Pressigny material is present at all. The industry is dominated (almost 50%) by fine-grained flints imported from the foothills of the Jura mountains 80–150 km to the north, especially "Kimmeridgien," a light-colored grey flint which often patinates black. This material seems to have been flaked on site (as opposed to the Grand-Pressigny flint at Saunerie, which was mostly imported as blades) using prismatic blade technologies.

Alle-Pré Monsieur

This open-air Mousterian site was discovered in 1992 during construction of the trans-Jura autoroute (Stahl Gretsch and Detrey 1999). It is located on a slope bordering the alluvial plain of the Allaine River, in a valley of the Jura Mountains

of western Switzerland. During the two seasons of excavation, over 100,000 worked lithics were recovered from approximately 157 m^2 and 12 archaeological layers. Fauna was unfortunately not preserved. Taphonomic issues include slippage of some of the artifact-bearing sediments downslope, which reversed the stratigraphy in several instances; absolute dating was attempted but failed. Nevertheless, a Mousterian affiliation for the site is possible due to the large percentage of Levallois cores and typical Mousterian retouched flake tools such as sidescrapers and déjeté scrapers. The most abundant archaeological layer, layer 2, which has been suggested by sedimentological analyses to date to the Eemian, or first portion of MIS 5, was used in this study. This layer yielded over 28,000 lithics, of which over 700 are Levallois flakes and 1,500 are retouched tools. The layer also yielded over 2,000 cores, half of them Levallois. One of us (G.F.M.) studied the entire retouched assemblage from this level and typed it according to Bordes' (1961) typology.

Selection of Artifacts for Inclusion in the Study

Many more artifacts were studied and photographed (see Methods) than were included in the analysis. The selection of artifact types for inclusion here was done only after all the assemblages had been studied. The reason for this was a desire to compare, as much as possible, the variance between similar tool types across different sites and time periods. Thus, once counts were tallied and the types most common across the assemblages were identified, all the artifacts from those types were included in this analysis.

Methods

We used 2D landmarks to capture and quantify the variation in shape of different tool types from different sites. Artifact shapes were collected from digital photographs of 297 artifacts from the four sites. Artifacts from Auvernier-Port and Auvernier-la-Saunerie were photographed at the Laténium museum in Neuchâtel using a Nikon D200 camera, macro lens, and lighting apparatus generously provided by the museum. Artifacts from Monruz were photographed at the Laténium annex using a Canon PowerShot A95 camera mounted on a light box. Artifacts from Pré Monsieur were photographed using the same equipment at the Office of Culture of the Jura canton in Porrentruy.

Orientation of the Artifacts and Location of the Landmarks

Since stone tools have few true landmarks, in the sense of "homologous anatomical loci that do not alter their topological positions relative to other landmarks" (Zelditch et al. 2004, p. 24), locating landmarks was a challenge. In fact, other than

the point of percussion and possibly the end points of the platform, there are no landmarks that can reliably be found on all stone tools. Since this study was concerned with retouched tools, we used a series of semilandmarks oriented on the artifacts according to tool axis. Tool axis was defined visually as the line bisecting the tool along its axis of maximum symmetry. While a more common way of orienting lithic tools is along the flaking axis of the tool blank, the removal of the platform on many of the tools precluded the use of this method.

The endpoints of the axis of tool symmetry provided two type II landmarks (Bookstein 1991). In order to better capture the tool morphology in a repeatable and consistent manner, however, a "comb" (see Fig. 4.1) with 12 equally spaced lines was applied to the photograph of each artifact, with a perpendicular line along the tool axis. Additional type III semilandmarks were thereby defined as the points at which the lines of the comb intersect the periphery of the artifact (all data are available for viewing online, see Monnier and McNulty 2009).

Combs were generated on digitized photographs using the software MakeFan6 (Sheets 2003), and landmarks were placed with a stylus using a Gateway Tablet notebook PC running tpsDig (Rohlf 2006). To calculate mean configurations and to visualize shape differences, landmarks for all artifacts within a tool type from a single site (e.g., backed bladelets from Monruz) were separately superimposed by generalized Procrustes analysis (Gower 1975; Bookstein 1991; Goodall 1991; Dryden and Mardia 1998) in the software CoordGen (Sheets 2003). Since there is no consensus on whether one should allow semilandmarks to "slide" during superimposition, both methods were tried in this study and the impact found to be negligible. Results reported here are based on semilandmarks that were not slid. Superimposed landmark configurations for each tool type from each site are illustrated in Figs. 4.2–4.9.

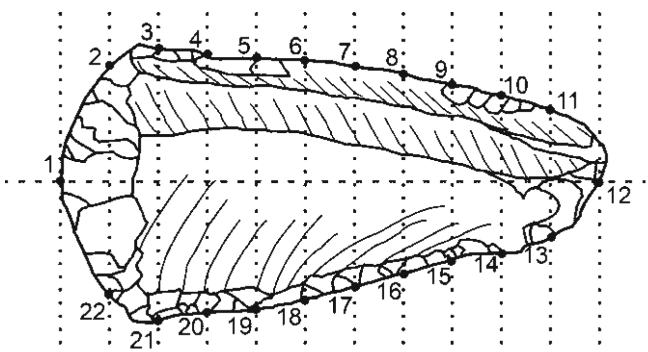

Fig. 4.1 Position of landmarks on each artifact according to the placement of "comb" along the axis of maximum symmetry of tool

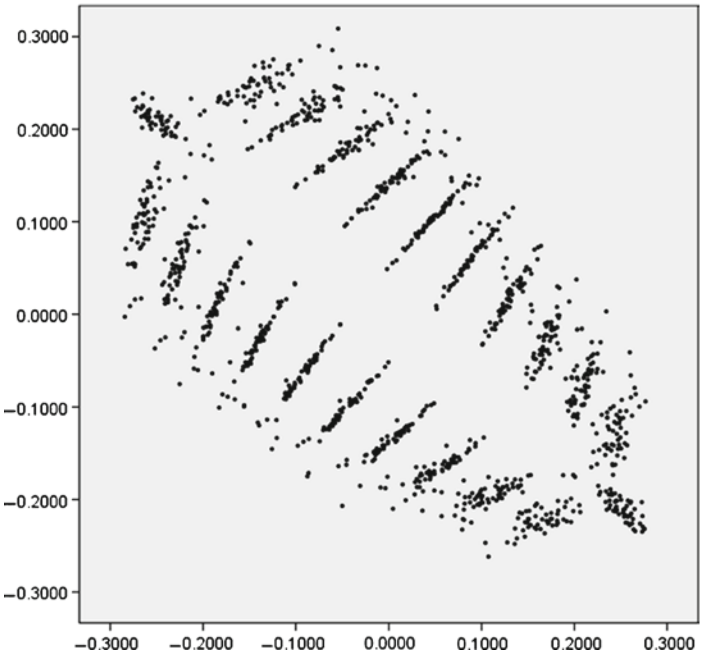

Fig. 4.2 Superimposed landmark configurations for Auvernier-Port retouched blades ($N=59$)

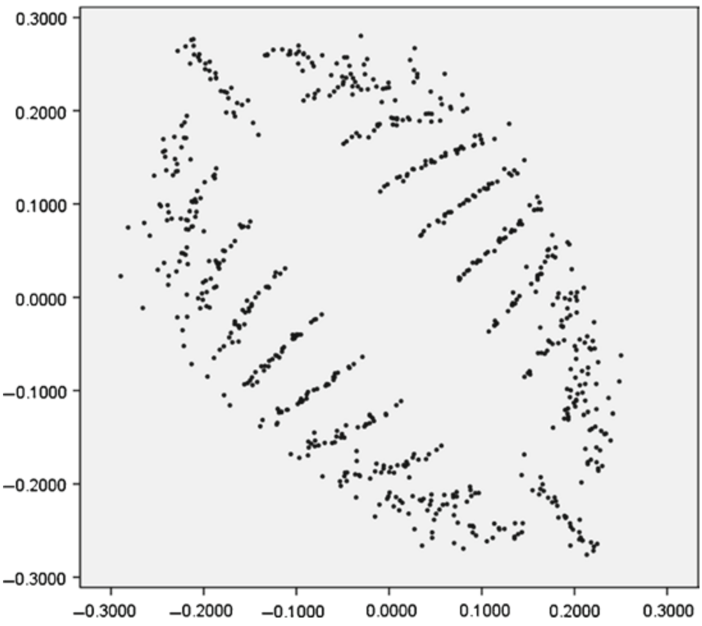

Fig. 4.3 Superimposed landmark configurations for Auvernier-Port endscrapers ($N=32$)

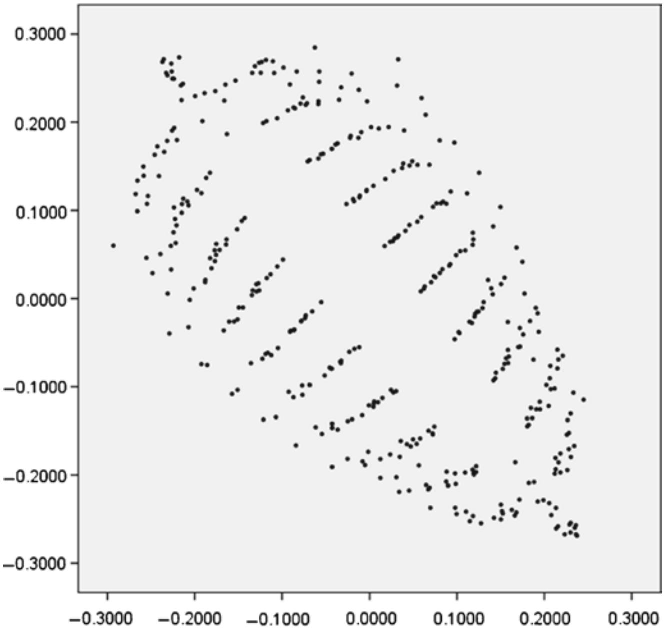

Fig. 4.4 Superimposed landmark configurations for Auvernier-Saunerie retouched blades ($N=18$)

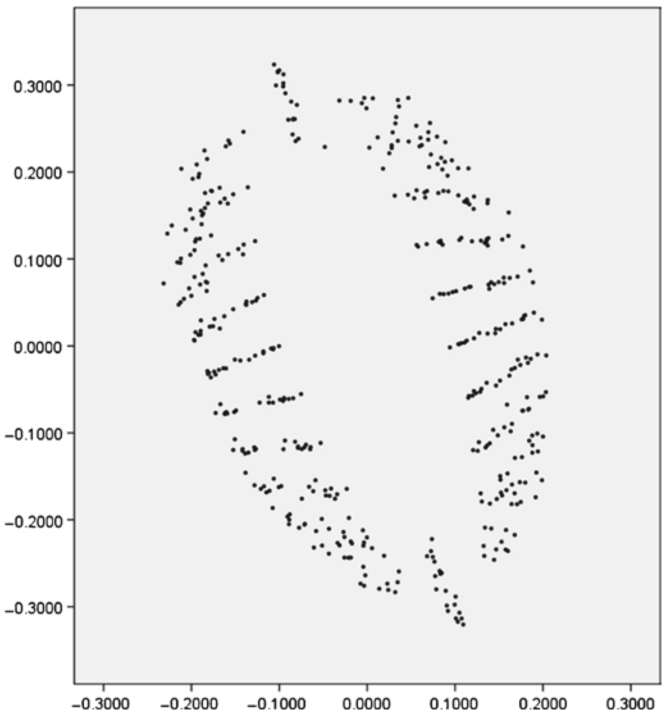

Fig. 4.5 Superimposed landmark configurations for Auvernier-Saunerie endscrapers ($N=20$)

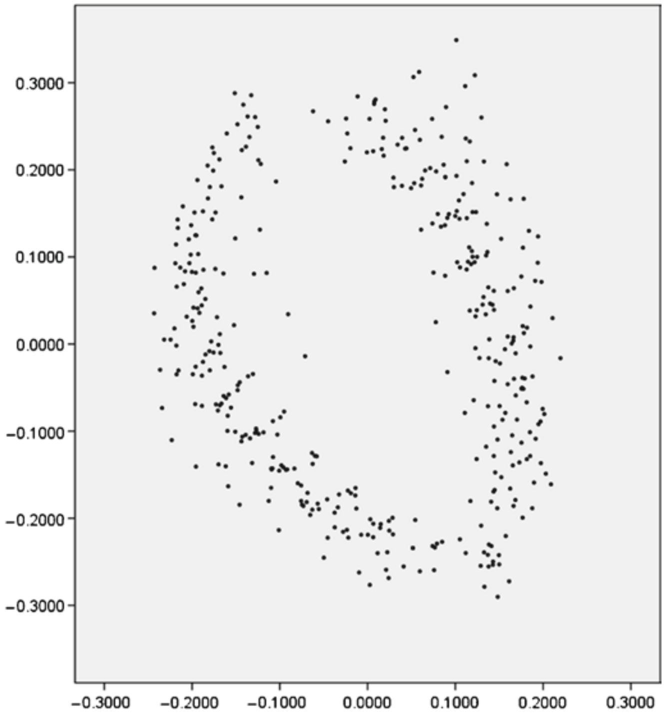

Fig. 4.6 Superimposed landmark configurations for Auvernier-Saunerie unifacially retouched flakes ($N = 18$)

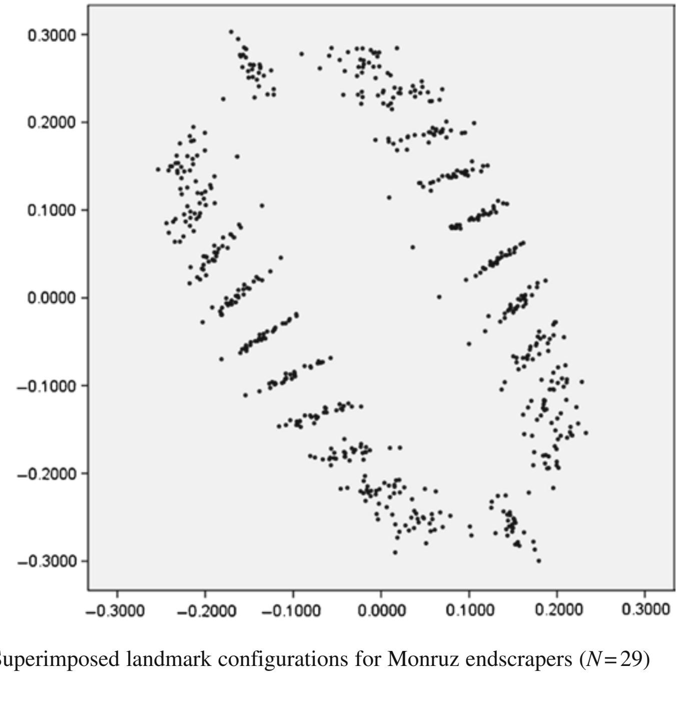

Fig. 4.7 Superimposed landmark configurations for Monruz endscrapers ($N = 29$)

Fig. 4.8 Superimposed landmark configurations for Monruz backed bladelets ($N=82$)

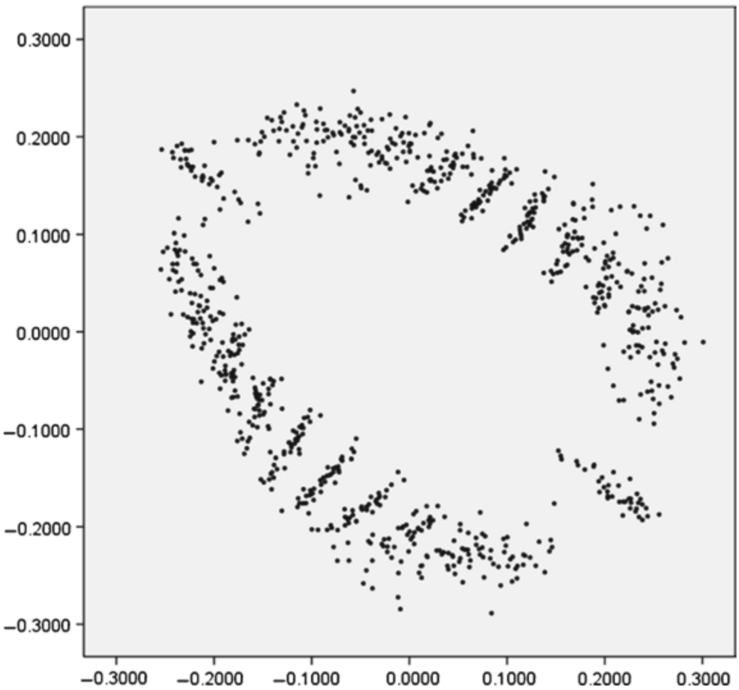

Fig. 4.9 Superimposed landmark configurations for Pre Monsieur convex single sidescrapers ($N=39$)

Calculation of Shape Variance

Since tool variation may not be comparable from one tool type to the next, specimens were separated into categories according to maximum comparability of tool type. This resulted in three sets of comparable tool types which span multiple time periods. Set 1 contains the endscrapers from Monruz, Auvernier-Saunerie, and Auvernier-Port. Set 2 contains the types "retouched flakes" from Auvernier-Saunerie and "single convex sidescrapers" from Pré Monsieur. Set 3 contains retouched blades from Auvernier-Saunerie and Auvernier-Port, and backed bladelets from Monruz.

The first step in evaluating the association between degree of standardization and behavioral modernity was to calculate the total variance in all superimposed landmark configurations for each tool type at each site. Mathematically, this variance is equivalent to the average Procrustes squared distance between each specimen in the category and the category mean configuration. These values summarized the amount of shape difference, i.e., the degree of standardization, exhibited for each tool type at each site. To determine whether standardization in comparable tool types (i.e., within but not between sets) was significantly different by locality, we applied a non-parametric Kruskal–Wallis test to both set 1 and set 3 tools, with specimens' Procrustes distances to their locality means as the dependent variable. Significant results were further elucidated by post hoc pairwise tests.

Differences in standardization between pairs of localities within a tool set were tested using non-parametric permutation tests. Because unequal sample sizes can significantly affect the results of these tests (McNulty et al. 2006), permutations were based on randomly generated balanced samples such that permuted groups had an equal probability of being populated by specimens from either test group. Permutation tests were carried out in SAS 9.1 based on programming code modified from McNulty (2005). Importantly, permutations were not done on the coordinate data, as this would involve calculating the means of permuted groups and thereby artificially inflating the variance within these randomized samples due to potential mean shape differences between sites. Instead, permutations were done specifically on the component of variance associated with each specimen, i.e., its Procrustes squared distance to its original group mean. Each permutation test was repeated 10,000 times, generating a probability distribution from which we tested the null hypothesis that the original difference in variance between the two groups was sampled from a common variance shared by both groups. Corrections for multiple comparisons were not used due to the small number of comparisons (not more than three for any tool type), and with only one exception significant p-values were well below the threshold of the most conservative (e.g., Bonferroni) corrections. In no case were experiment-wise alpha values above 0.05.

Results

The variances in shape within each sample are summarized in Table 4.1. The lowest variances occur among Neuchâtel-Monruz' backed bladelets (var = 0.008) and end-scrapers (var = 0.015). The highest variances come from the Neolithic sites, especially Auvernier-Saunerie retouched blades (var = 0.035), unifacially retouched flakes (var = 0.031), and endscrapers (var = 0.028). The endscrapers from Auvernier-Port (var = 0.034) are also among the most variable tool type included in the study. Interestingly, the variance among sidescrapers from Pré Monsieur falls in the middle of this range (var = 0.022). In other words, the least variable (most standardized) tool types are those from the Upper Paleolithic site; the most variable are from the Neolithic sites. Nevertheless, such comparisons across tool types may not be informative since one might expect differences in the amount of standardization in tools of different shapes and functions.

Results of significance tests within tools sets (Table 4.2) are highly pertinent, however. Both endscrapers and blade/bladelet tool sets exhibited significant differences among localities. Pairwise permutation tests demonstrated which localities

Table 4.1 Summary information and variances for each sample

	Site	Period	Likely Hominin	Tool type	*N*	Variance
Set 1	Auvernier-Saunerie	Late Neo	Modern	Endscrapers	20	0.028
	Auvernier-Port	Mid-Neo	Modern	Endscrapers	32	0.034
	Neuchâtel-Monruz	UP	Modern	Endscrapers	29	0.015
Set 2	Auvernier-Saunerie	Late Neo	Modern	Retouched flakes	18	0.031
	Pré Monsieur	MP	Neanderthal	Sidescrapers	39	0.022
Set 3	Auvernier-Saunerie	Late Neo	Modern	Retouched blades	18	0.035
	Auvernier-Port	Mid-Neo	Modern	Retouched blades	59	0.024
	Neuchâtel-Monruz	UP	Modern	Backed bladelets	82	0.008

Table 4.2 *p*-Values for Kruskal–Wallis tests of differences in variance within tool sets and for permutation tests of differences between samples in each set (*p*-values significant at the 0.05 level are in **bold**)

	Samples compared	Tool type	Permutation test results
Set 1 ($p = 0.0048$)	Saunerie vs. Port	Endscrapers	$p = 0.4848$
	Monruz vs. Port	Endscrapers	$\mathbf{p = 0.0065}$
	Monruz vs. Saunerie	Endscrapers	$\mathbf{p = 0.0366}$
Set 2	Pré Monsieur vs. Saunerie	Sidescrapers vs. retouched flakes	$p = 0.2370$
Set 3 ($p < 0.0001$)	Saunerie vs. Port	Retouched blades	$p = 0.2827$
	Monruz vs. Port	Backed bladelets vs. retouched blades	$\mathbf{p < 0.0001}$
	Monruz vs. Saunerie	Backed bladelets vs. retouched blades	$\mathbf{p < 0.0001}$

Kruskal–Wallis *p*-values are given next to the set number. Set 2 has only two samples and was therefore only tested using a pairwise permutation test

are different for these sets and provided a significance test for the sidescrapers/retouched flakes. These results indicate that the variances among tool types from Monruz are always significantly different from the variances among comparable tool types from the Neolithic contexts. More precisely, among both endscrapers and retouched blades, the artifacts from Monruz are significantly less variable in shape (i.e., more standardized) than those from either Auvernier-Port or Auvernier-Saunerie. Regarding the Middle Paleolithic assemblage from Pré Monsieur, there is unfortunately no direct comparison that can be made between tools from this site and any from Monruz. However, we decided to compare convex sidescrapers from Pré Monsieur with retouched flakes from Auvernier-Saunerie. While these tool types are not identical, we deemed them to be comparable, since they both involve lateral retouch on flakes. The difference between the two variances was not significant. In other words, the Neolithic retouched flakes are *not* more standardized than the Middle Paleolithic sidescrapers, which is contrary to the expectations of the standardization hypothesis, in which tools created by modern humans should be more standardized than those created by Neanderthals. While it is tempting to interpret this result as meaning that both Pré Monsieur and Saunerie tools *lack* standardization, it in fact demonstrates that they are equally standardized.

Discussion

The idea of standardization is intuitively satisfying in the context of cultural evolution, particularly when considering more than two million years of lithic technological change. However, like any trait associated with human evolution, general trends that seem obvious when one considers the broad scale of change may lose explanatory power when applied to the smaller branches or segments of our lineage. Add to this the complexity of cultural adaptation and reticulation and such trends become more difficult to apply generally.

That behaviorally modern humans would have a greater capacity to envision and shape stone tools is an attractive hypothesis that coincides with historical concepts of modernity. But to support this hypothesis – specifically to provide evidence that modern humans had a superior ability to form "mental templates" and "impose form" on their tools – one should be able to demonstrate this broadly, if not exclusively, across multiple modern technologies, multiple modern cultures, multiple tool functions, and multiple raw materials. Moreover, evidence should address the myriad alternative explanations, such as function, technology (Chase 1991), raw material, reduction, and even typology (Dibble 1989) that may also explain variance in standardization (see also Monnier 2006b). Unfortunately, such a test is difficult to conceive. One cannot make reasonable comparisons in standardization between different types of tools, yet the very nature of cultural change means that there is little overlap in tool types between MP and UP assemblages.

This project represents one specific test of the hypothesis that standardization is a feature of behaviorally modern humans, and it builds on work by previous researchers (Chazan 1995; Wurz 1999; Marks et al. 2001; Monnier 2006b).

Unlike the studies by Chazan (1995) and Wurz (1999), however, our results do not support the notion that standardization reflects linguistic or mental categories. We emphasize that other factors must be considered before differences in standardization can be applied to cognitive factors. Secondly, this study methodologically improves upon previous studies of standardization (Marks et al. 2001; Monnier 2006b) by applying a new measure of artifact shape which is much more comprehensive than the traditional linear measurements.

The most salient result is the lack of difference in standardization between the MP Pré Monsieur sidescrapers and the retouched flakes from the Neolithic site of Auvernier-Saunerie. According to the standardization hypothesis, we would expect the Neolithic tools, which were made by modern humans, to be more standardized than the Middle Paleolithic ones, which were made by Neanderthals. This shows that our intuitions are not always correct. An explanation for this result can be found by studying the results of the variance differences between the UP site Monruz and the Neolithic Auvernier sites. For both tool types (endscrapers and backed bladelets), the Monruz tools are more standardized than the corresponding Neolithic tools. We believe that there is a simple explanation for this result. The Monruz tools appear to be highly specialized: they are made on imported, high-quality raw material which was knapped into series of blades and bladelets (Bullinger et al. 2006b) and most likely hafted. The Neolithic tools were also made on high-quality, exotic raw material (in the case of Auvernier-Saunerie, on Grand-Pressigny flint from France, over 400 km away) and some of them were certainly hafted in wooden shafts (which we know from instances of preserved hafted retouched blades and flakes). However, the Neolithic retouched blades and endscrapers are much more highly reduced than the Upper Paleolithic artifacts. This is especially true at Auvernier-Saunerie, where the large imported blades of Grand-Pressigny flint were heavily reworked, often around the entire periphery of the tool. These blades were sometimes heavily retouched laterally, achieving the morphology of long, narrow "rods," while others were truncated and turned into endscrapers (with retouched lateral edges). There is continuous overlap between these two categories (retouched blades and endscrapers), much as has been demonstrated for Mousterian tool types by Dibble (1984). This overlap could therefore introduce greater variability within the type categories in the Auvernier sites than exists at Monruz. These results make it difficult to reconcile standardization with a better capacity for mental imaging or imposition of form; presumably, the Neolithic and Magdalenian populations had similar mental and behavioral capabilities. Yet their production of similar forms, forms that ought to derive from equally detailed mental templates, shows a significant difference in standardization.

Ultimately, the idea of "standardization" seems to be a poor arbiter for which human groups were behaviorally modern and which groups were not. In that sense, there is little evidence to suggest that modern humans had a greater mental capacity to generate idea templates or to impose these ideas on their natural world. The factors leading to standardization as well as the behavioral and cognitive differences between early modern humans and their relatives comprise an exciting and fruitful avenue of research. However, the traditional imposition of a linear form on the *concept* of standardization

has obscured the real diversity that was present in these groups, and impeded our knowledge of the generative processes that resulted in modern human behavior.

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References

Affolter, J., 2002. *Provenance des silex préhistoriques du Jura et des regions limitrophes*. Service et Musée cantonal d'archéologie (Archéologie neuchâteloise, 28; 2 vol.), Neuchâtel.

Arnold, B., 2006. Annexe 2, Une operation exceptionnelle: le prélèvement et le transport d'un volume archéologique de 400 tonnes. In *Le site magdalénien de Monruz, 1. Premiers elements pour l'analyse d'un habitat de plein air*, edited by J. Bullinger, D. Leesch and N. Plumettaz, pp. 217–222. Service et Musée cantonal d'archéologie (Archéologie neuchâteloise, 33), Neuchâtel.

Barham, L., 2002. Backed tools in Middle Pleistocene central Africa and their evolutionary significance. *Journal of Human Evolution* 43: 585–603.

Bar-Yosef, O. and Kuhn, S.L., 1999. The big deal about blades: Laminar technologies and human evolution. *American Anthropologist* 101: 322–338.

Belfer-Cohen, A., 1995. Comment on "The Language Hypothesis for the Middle-to-Upper Paleolithic Transition: An Examination Based on a Multiregional Lithic Analysis" by M. Chazan. *Current Anthropology* 36: 758–759.

Boiseaubert, J.-L., 1982. Le Néolithique Moyen de la Saunerie Fouilles 1972–1975. *Cahiers d'archéologie romande* no. 23, Lausanne.

Bookstein, F.L., 1991. *Morphometric Tools for Landmark Data: Geometry and Biology*. Cambridge University Press, Cambridge.

Bookstein, F.L., Slice, D.E., Gunz, P. and Mitteroecker, P., 2004. Anthropology takes control of morphometrics. *Coll. Antropol*. 28 (Suppl. 2), 121–132.

Bordes, F., 1961. Typologie du Paléolithique ancien et moyen. Paris: Centre National de la Recherche Scientifique.

Bullinger, J., Affolter, J. and Cattin, M.-I., 2006. L'industrie lithique. In *Le site Magdalénien de Monruz, 1. Premiers elements pour l'analyse d'un habitat de plein air*, edited by J. Bullinger, D. Leesch and N. Plumettaz, pp. 75–100. Service et Musée cantonal d'archéologie (Archéologie neuchâteloise, 33), Neuchâtel.

Bullinger, J., Leesch, D. and Plumettaz, N., 2006. *Le site Magdalénien de Monruz, 1. Premiers elements pour l'analyse d'un habitat de plein air.* Service et Musée cantonal d'archéologie (Archéologie neuchâteloise, 33), Neuchâtel.

Byers, A.M., 1994. Symboling and the Middle-Upper Palaeolithic transition: a theoretical and methodological critique. *Current Anthropology* 35: 369–400.

Chase, P.G., 1991. Symbols and Palaeolithic artefacts: style, standardisation, and the imposition of arbitrary form. *Journal of Anthropological Archaeology* 10: 193–214.

Chazan, M., 1995. The language hypothesis for the middle-to-upper paleolithic transition. *Current Anthropology* 36: 749–768.

Commont, V., 1908. Les industries de l'ancien Saint-Acheul. *L'Anthropologie* 19: 527–572.

Corbey, R. and Roebroeks, W., 1995. Comment on "The Language Hypothesis for the Middle-to-Upper Paleolithic Transition" by M. Chazan. *Current Anthropology* 36: 759.

Deacon, H.J., 1989. Late Pleistocene palaeoecology and archaeology in the southern Cape, South Africa. In *The Human Revolution: Behavioural and Biological Perspectives on the Origins of Modern Humans*, edited by P. Mellars and C. Stringer, pp. 547–564. Edinburgh University Press, Edinburgh.

Deetz, J., 1967. *Invitation to Archaeology*. The American Museum of Natural History. The Natural History Press, Garden City, New York.

D'Errico, F., 2003. The invisible frontier. A multiple species model for the origin of behavioral modernity. *Evolutionary Anthropology* 12: 188–202.

Dibble, H., 1984. Interpreting typological variation of Middle Paleolithic scrapers: Function, style, or sequence of reduction? *Journal of Field Archaeology* 11: 431–436.

Dibble, H., 1989. The implications of stone tool types for the presence of language during the Middle Paleolithic. In *The Human Revolution: Behavioural and Biological Perspectives on the Origins of Modern Humans*, edited by P. Mellars and C. Stringer, pp. 415–432. Edinburgh University Press, Edinburgh.

Dryden, I.L. and Mardia, K.V., 1998. *Statistical Shape Analysis*. John Wiley, London.

Goodall, C.R., 1991. Procrustes methods and the statistical analysis of shape. *Journal of the Royal Statistical Society B* 53: 285–340.

Gower, J.C., 1975. Generalised Procrustes analysis. *Psychmetrika* 40: 33–50.

Graves-Brown, P.M., 1995. Comment on "The Language Hypothesis for the Middle-to-Upper Paleolithic Transition" by M. Chazan. *Current Anthropology* 36: 759–760.

Henshilwood, C.S. and Marean, C., 2003. The origin of modern human behavior: critique of the models and their test implications. *Current Anthropology* 44: 627–651.

Holloway, R., 1969. Culture: A human domain. *Current Anthropology* 10: 395–412.

Honegger, M., 2001. *L'industrie lithique taillée du Néolithique moyen et final en Suisse*. CRA Monographies 24. CNRS, Paris.

Klein, R.G., 1995. Anatomy, behavior, and modern human origins. *Journal of World Prehistory* 9: 167–198.

Klein, R.G., 2000. Archaeology and the evolution of human behavior. *Evolutionary Anthropology* 9: 17–36.

Klein, R.G., 2008. Out of Africa and the evolution of human behavior. *Evolutionary Anthropology* 17: 267–281.

Lycett, S.J., 2007. Is the Soanian techno-complex a Mode 1 or Mode 3 phenomenon? A morphometric assessment. *Journal of Archaeological Science* 34: 1434–1440.

Lycett, S.J., von Cramon-Taubadel, N. and Foley, R.A., 2006. A crossbeam co-ordinate caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33: 847–861.

Lycett, S. and von Cramon-Taubadel, N., 2008. Acheulean variability and hominin dispersals: a model-bound approach. *Journal of Archaeological Science* 35: 553–562.

Marks, A.E., Hietala, H. and Williams, J.K., 2001. Tool standardization in the Middle and Upper Paleolithic: a closer look. *Cambridge Archaeological Journal* 11: 17–44.

McBrearty, S., 2007. Down with the revolution. In *Rethinking the Human Revolution, New Behavioural and biological Perspectives on the Origin and Dispersal of Modern Humans*, edited by P. Mellars, K. Boyle, O. Bar-Yosef and C. Stringer, pp. 133–152. McDonald Institute Monographs, Cambridge.

McBrearty, S. and Brooks, A., 2000. The revolution that wasn't. A new interpretation of the origin of modern human behavior. *Journal of Human Evolution* 39: 453–563.

McNulty, K.P., 2005. Permutation procd.sas, updated: 7 December, 2007. *SAS for Geometric Morphometrics*. Retrieved 20 December, 2008, from http://anthropologylabs.umn.edu/html/sas_for_geometric_morphometric.html.

McNulty, K., Frost, S. and Strait, D., 2006. Examining affinities of the Taung child by developmental simulation. *Journal of Human Evolution* 51: 274–296.

Mellars, P., 1989a. Major issues in the emergence of modern humans. *Current Anthropology* 30: 349–385.

Mellars, P., 1989b. Technological changes at the Middle-Upper Palaeolithic transition: economic, social and cognitive perspectives. In *The Human Revolution: Behavioural and Biological Perspectives on the Origins of Modern Humans*, edited by P. Mellars and C. Stringer, pp. 338–365. Edinburgh University Press, Edinburgh.

Mellars, P., 1991. Cognitive changes and the emergence of modern humans in Europe. *Cambridge Archaeological Journal* 1: 63–76.

Mellars, P., 1996. *The Neanderthal Legacy: An Archaeological Perspective from Western Europe*. Princeton University Press, Princeton.

Mellars, P., 2007. Rethinking the human revolution: Eurasian and African perspectives. In *Rethinking the Human Revolution, New Behavioural and biological Perspectives on the Origin and Dispersal of Modern Humans*, edited by P. Mellars, K. Boyle, O. Bar-Yosef and C. Stringer, pp. 1–14. McDonald Institute Monographs, Cambridge.

Monnier, G., 1995. Comment on "The Language Hypothesis for the Middle-to-Upper Paleolithic Transition" by M. Chazan. *Current Anthropology* 36: 761–762.

Monnier, G., 2006a. The Lower/Middle Paleolithic periodization in Western Europe: An evaluation. *Current Anthropology* 47: 709–744.

Monnier, G., 2006b. Testing retouched flake tool standardization during the Middle Paleolithic: patterns and implications. In *Transitions Before the Transition: Evolution and Stability in the Middle Paleolithic and Middle Stone Age*, edited by E. Hovers and S.L. Kuhn, pp. 57–84. Kluwer Press, New York.

Monnier, G., 2007. Middle Paleolithic Scraper morphology, flaking mechanics, and imposed form: revisiting Bisson's 'Interview with a Neanderthal'. *Cambridge Archaeological Journal* 17: 341–350.

Monnier, G. and McNulty, K., 2009, Morphometrics data from Paleolithic and Neolithic sites. http://www.anthropologylabs.umn.edu/eal/research/GillianeMonnier.php.

de Mortillet, G., 1883. *Le Préhistorique: Antiquité de l'Homme*. C. Reinwald, Paris.

Nowell, A. 2002. Coincidental factors of handaxe morphology. *Behavioral and Brain Sciences* 25: 413–414.

Rohlf, F.J., 2006. *TpsDig*, v. 2.10. Ecology and Evolution Department, SUNY Stony Brook, New York, USA.

Ronen, A. (ed.), 1982. *The Transition from Lower to Middle Paleolithic and the Origin of Modern Humans* (BAR International Series 151) BAR, Oxford.

Shea, J., 1995. Comment on "The Language Hypothesis for the Middle-to-Upper Paleolithic Transition" by M. Chazan. *Current Anthropology* 36: 762–763.

Sheets, H.D., 2003. *IMP – Integrated Morphometrics Package*. Dept. of Physics, Canisius College, 2001 Main St. Buffalo, NY 14208. http://www.canisius.edu/~sheets/morphsoft.html

Stahl Gretsch, L.-I. and Detrey, J., 1999. Le Site Moustérien d'Alle, Pré Monsieur (Jura, Suisse). Office du patrimoine historique et Société jurassienne d'Emulation, Porrentruy. *Cahier d'archéologie jurassienne* 9.

Trigger, B., 1996. *A History of Archaeological Thought*. Second Edition. Cambridge University Press, Cambridge.

Van Peer, P., 1995. Comment on "The Language Hypothesis for the Middle-to-Upper Paleolithic Transition" by M. Chazan. *Current Anthropology* 36: 764–765.

Wurz, S., 1999. The Howiesons Poort backed artefacts from Klasies River: An argument for symbolic behaviour. *The South African Archaeological Bulletin* 169: 38–50.

Zelditch, M., Swiderski, D., Sheets H.D. and Fink, W.L., 2004. *Geometric Morphometrics for Biologists: A Primer*. Elsevier Academic Press, San Diego.

Chapter 5
The Quantitative Analysis of Mobility: Ecological Techniques and Archaeological Extensions

Matt Grove

Abstract This paper provides an overview of techniques for the quantitative analysis of mobility derived from mathematical ecology. Focusing on the Lévy distribution as a model for movement data, a number of methods for identifying power laws are assessed. These methods are applied to a dataset gathered by Yellen (Archaeological Approaches to the Present: Models for Reconstructing the Past, 1977) during research among the Dobe !Kung and allow the complete mathematical description of the movement pattern of that group. Results suggest that the group moves between resource patches which are power-law distributed in size but that their camp relocation distances follow a lognormal distribution. These results are interpreted by reference to the "complete radius leapfrog pattern" described by Binford (J Anthropol Archaeol 1:5–31, 1982). In order to extend the study of mobility as practiced by ecologists to the data encountered in the archaeological record, a novel simulation methodology is developed that relates step-length distributions to the distributions of intersite distances in landscape-level archaeological samples. This methodology is discussed with regard to its archaeological implications and certain social and cognitive correlates of specific mobility strategies.

Introduction

The distribution of lithics in geographical space is in many ways the basic data of archaeology (Isaac 1981). Furthermore, such data are available to ground hypotheses at multiple scales; from typological analyses, through site function and settlement pattern studies and beyond into social and cognitive reconstructions of prehistoric life, the underlying spatial organization of the archaeological record is of paramount importance. It is vital, therefore, that our conceptions of archaeological space are situated

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within a sound quantitative framework that allows us to compare different temporal periods and geographical regions with a view to accurately elucidating trends and patterns. Central to this is the need to relate static archaeological sites to the dynamic processes responsible for their formation. In other words, models with which to relate the activities of prehistoric foragers to the material remains excavated are essential. Though contemporary ecological analyses employ models, in the form of stochastic processes such as random walks, that provide information on characteristic foraging patterns of extant species, archaeologists are faced with the problem of a further inferential gap that exists between the modern analogue and the prehistoric reality. It will be argued in the course of this paper that we can traverse this gap via a judicial synthesis of ecological techniques and more traditional archaeological analyses.

A fundamental aspect of the approach taken here is the use of various forms of random walk to model and explain the landscape-scale movements of prehistoric foragers. Such approaches are rarely applied in archaeological studies, though the recognition of their potential is not new. David Clarke was aware as early as the mid-1960s of the potential applications of stochastic simulation to archaeological problems as diverse as the "diffusion of cultural elements" and the "interpretation of the processes behind the archaeologically observed distribution patterns of prehistoric artifacts" (Clarke 1968:442). This latter topic and a general concern with how best to explain spatial patterning in the archaeological record were central elements of Clarke's research program, reflected not only in several key publications (Clarke 1968, 1972, 1977a, b, further papers in Clarke 1979) but also in the parallels between the development of his work and that of the New Geography's principal exponents (e.g., Haggett 1965; papers in Chorley and Haggett 1967; Haggett et al. 1977). The geographer's desire to quantify the use of space, exemplified by Haggett's *Locational Analysis* (1965), was echoed by a desire to bring strict scientific reasoning to the discipline of archaeology. It is notable in this vein that both Clarke and Lewis Binford, the leading proponent of the New Archaeology in the USA, devoted early publications to the spatial analysis of archaeological and anthropological materials (e.g., Clarke 1977b; Binford 1982).

The current paper applies a particular type of stochastic process, the random walk, to the examination of recent anthropological data, with the aim of demonstrating that such processes retain their explanatory value when directed toward the archaeological record. Though the concept of the random walk appeared soon after the turn of the century (Pearson 1905; Rayleigh 1905), and was appropriated immediately by physicists (e.g., Einstein 1905, 1906), it did not filter through to the biological sciences in earnest until the early diffusion studies of the 1950s (e.g., Skellam 1951; Reid 1953; Patlak 1953a, b). Hagerstrand's (1967) pioneering geographical work on diffusion followed before Clarke (1972) brought the technique to the attention of archaeologists. Clarke's recognition of the potential significance of random walks for "modeling the colonization, movement or diffusion of archaeological artifacts and sites" (Clarke 1972:20) was followed by the specific suggestion that successive settlement site movements of fifth millennium BC agriculturalists in a homogeneous loess landscape would be an ideal testing ground for such a method (Clarke 1972:20ff.). Though this latter case study was not pursued, the idea of random walk applications in archaeology was adopted by subsequent textbooks on analytical techniques (e.g., Hodder and Orton 1976).

Despite (or perhaps due to) Clarke's appreciation of and eagerness to exploit such cutting-edge techniques, his books "were usually ignored by the most traditional-minded of British archaeologists" (Hammond 1979:7). Sadly, the aversion to computationally complex or formal mathematical approaches remains in some quarters and is manifest in various forms of stubborn ignorance that collectively inhibit the progress of archaeology as a science. The current volume is in many ways an attempt to address this problem, and the current chapter attempts to promote the use of a particular set of mathematical techniques in the reconstruction of prehistoric foraging. Random walk models of various kinds are employed regularly in analyses of animal movement data with a particular form, the Lévy Walk, emerging in recent times as the dominant and most useful model in numerous scenarios. The following section provides a brief overview of random walk models in ecology, focusing on recent applications of the Lévy walk model, and in particular on its use in primatology and the human sciences. "Lévy Walks in Hunter-Gatherers" reanalyses a well-known hunter-gatherer movement dataset to test for the presence of Lévy mobility and examines the results with reference to an established anthropological model of forager relocation. "Archaeological Extensions and Implications" extends this analysis and provides a method for the direct application of random walk models to the archaeological record. "Discussion" outlines some ongoing debates in the study of mobility as they pertain to the methodology of "Archaeological Extensions and Implications," and "Conclusions" briefly summarizes the key conclusions.

Lévy Walks

Ecological Foundations

The essential motivation behind the development of random walk models in ecology has been to provide a simple means by which to quantify and describe animal movement; breaking down a movement path into discrete, mathematically tractable elements allows a researcher to communicate those elements effectively and to compare them with similar data from other species. Though such models have a long history, only recent developments are considered here. The interested reader should consult Berg (1983), Turchin (1998), or Rudnick and Gaspari (2004) for more detailed mathematical treatments and further information.

A random walk is a movement path broken down into three basic measurements; step length, turning angle, and waiting time (see Fig. 5.1). Simple random walks (SRWs) involve step lengths of one and random turning angles (i.e., angles distributed according to a circular uniform distribution), with waiting times often disregarded or implied to be constant. SRWs have recently been used to describe the movements of species including gophers (Benedix 1993), gazelles (Ward and Saltz 1994), wood mice (Blackwell 1997), and caribou (Schaefer et al. 2000), and form the basis of most models of biological diffusion (e.g., Skellam 1951; Reid 1953; Patlak 1953a; Okubo 1980; Turchin 1998). Until recently, most developments of this basic model involved modification of the turning angle distribution to

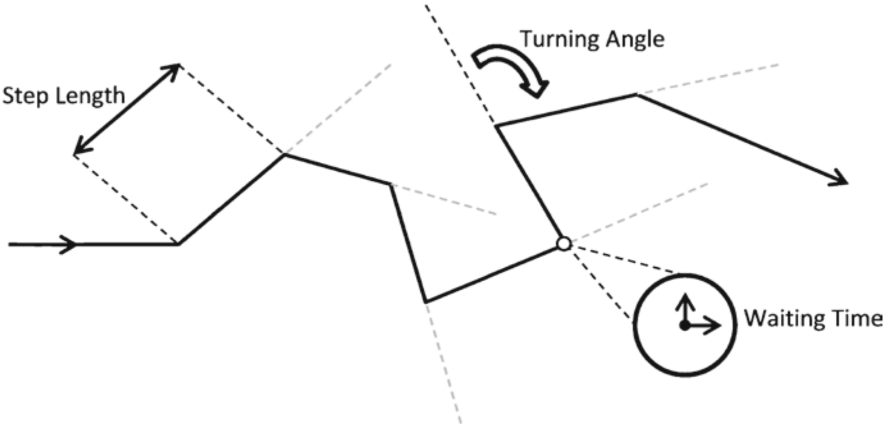

Fig. 5.1 A random walk is characterized mathematically by reference to the distributions of step lengths, turning angles and, less commonly, waiting times. Here, turning angles are measured relative to the previous trajectory, while waiting times are measured as the amount of time spent at the location of the turn. In the context of the current paper, such locations are best thought of as the sites at which a hunter-gatherer band either sets up camp or spends a nontrivial period of time in some subsistence-related activity that would leave archaeological traces

take into account the fact that many animals move with some form of directional bias. Thus, biased random walks (BRWs) are used to describe the movements of animals toward specific goals and are frequently employed to describe the foraging trajectories of aquatic and avian fauna (e.g., Grunbaum 1998; Bailey and Thompson 2006; Faugeras and Maury 2007; Reynolds et al. 2007a). Correlated random walks (CRWs), by contrast, are by far the most frequently used model for the movement of terrestrial animals (e.g., Skellam 1973; Kareiva and Shigesada 1983; Bovet and Benhamou 1988; Crist et al. 1992; Johnson et al. 1992; Bergman et al. 2000; Johnson et al. 2008). The distinction between the two is best understood by the fact that BRWs show long-term persistence in a given direction, while in CRWs only adjacent turning angles are correlated, and thus an animal could be operating any strategy from straight line to spiral search.

In contrast to both BRWs and CRWs, Lévy Walks involve a modification of the step-length distribution. Formally, the probability of a move of length l is distributed as:

$$p(l) = cl^{-\mu},\ l \geq l_{\min},\ 1 \leq \mu < 3 \tag{5.1}$$

Where, $l_{\min}$ is the minimum step length, and the constant $c = (\mu - 1)l_{\min}^{\mu-1}$ normalizes the distribution function to ensure that its integral from the minimum step length to infinity is 1. The truncation of μ is due to its effects on the additive distributions studied by Lévy (1937); when $\mu < 1$ the additive distribution cannot be normalized, while when $\mu \geq 3$, it converges to a Gaussian via the central limit theorem. Within the range specified, the additive distribution converges to a power law, producing the scale-free behavior that has prompted such interest among physicists and biologists

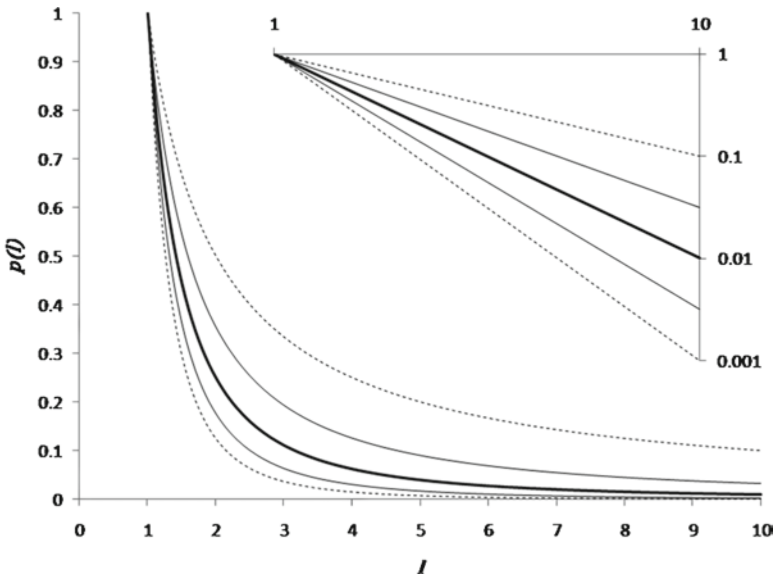

Fig. 5.2 The Lévy distribution, $p(l) = l^{-\mu}$, $1 < \mu < 3$. The *dotted lines* show the limits of the distribution at $\mu = 1$ (*upper curve*) and $\mu = 3$ (*lower curve*), whilst the *bold curve* indicates the distribution for $\mu = 2$, identified by Viswanathan and colleagues (1999) as the optimal value for random search. The *upper figure* displays the same series of curves on logarithmic scales

alike. The Lévy distribution for various μ values is graphed in Fig. 5.2. The turning angles of a LW are still most frequently modeled as being random, with the negative power law distribution described by Eq. 5.1 being applied to step lengths and, occasionally, to the waiting times. Empirical examples of LW behavior in the ecological literature are increasingly numerous (e.g., Levandowsky et al. 1997; Viswanathan et al. 2002; Bartumeus et al. 2002, 2003; Hays et al. 2006; de Knegt et al. 2007). The generally acknowledged first appearance of a reference to LWs in animal search behavior appeared only in 1986. Shlesinger and Klafter (1986), following a suggestion that some ants perform LW when searching for food in a new area, argue that this could afford them "a slight evolutionary advantage over ants performing other walks" (Shlesinger and Klafter 1986:283). Levandowsky and colleagues (1988a, b) found that microzooplankton follow three-dimensional LW and suggested that this is an optimal form of resource exploitation, while Cole (1995) discussed the distribution of stationary periods in fruit flies. However, the seminal publication of Viswanathan and colleagues (1996) on the flight patterns of the wandering albatross represents the first test of the then formative Lévy foraging hypothesis on an animal in its natural environment. Viswanathan and colleagues hypothesized that wandering albatross flights had evolved to be scale-invariant so as to efficiently harvest fractally distributed food resources on the ocean surface.

The albatross research was followed in 1999 by the paper that appears to have been the spur to the exponentially growing LW foraging literature (Viswanathan et al. 1999), in which Viswanathan and colleagues established via simulation that a LW with

an exponent of $\mu = 2$ forms an optimal search algorithm for static, randomly distributed, low-density resources. The simulation studies of Viswanathan and colleagues (1999, 2000, 2001, 2002) were complemented by empirical data on bumblebees and deer (Viswanathan et al. 1999), with both datasets showing LW behavior and thus demonstrating what are thought to be optimal search strategies. These data were followed by additional data on reindeer (Marell et al. 2002) and an extensive series of studies on search strategies in bees (Reynolds 2007, 2008; Reynolds and Frye 2007; Reynolds et al. 2007b, c) as well as papers reporting LW or LW-like behavior in soil amoebas (Levandowsky et al. 1997), microzooplankton (Bartumeus et al. 2003), jackals (Atkinson et al. 2002), albatrosses (Fritz et al. 2003), arctic seals (Austin et al. 2004), moths (Reynolds et al. 2007a), elephants (Dai et al. 2007), and goats (de Knegt et al. 2007). In addition to these empirical studies, a slew of papers highlighting theoretical advances have appeared since the 1999 watershed (e.g., Harnos et al. 2000; Ricotta 2000; da Luz et al. 2001; Alonso et al. 2002; Raposo et al. 2003; Hancock and Milner-Gulland 2006; Sims et al. 2006; Coscoy et al. 2007). Though doubts over the reality of LW behavior have persisted, particularly as regards the earlier case studies (see concerns expressed by Edwards et al. 2007; Sims et al. 2007; Benhamou 2007), a recent and expansive study by Sims and colleagues (2008) demonstrating LW in sharks, sea turtles, and penguins has shifted the focus of the debate from "whether animals perform [LW] to when and how often they use this strategy and why" (Bartumeus, quoted in Travis 2008; see also Viswanathan et al. 2008).

Lévy Walks in Primatology, Archaeology, and the Human Sciences

The phenomenal increase in the number of studies citing LW behavior in ecology has not been completely without parallel in the anthropological sciences. In the past 5 years, a small number of studies have appeared in anthropology and archaeology that employ the generic LW model as either an explanation of empirical data (Ramos-Fernandez et al. 2004; Brown et al. 2007) or a basis for simulation (Brantingham 2003, 2006). With the exception of the recent analysis of Dobe !Kung site relocation (Brown et al. 2007), the data for which forms the basis of "Lévy Walks in Hunter-Gatherers," these papers are briefly summarized here. Though the number of studies remains small, they show collectively the potential for the application of LW and scale-free methodologies to archaeological and anthropological datasets.

In the first of a truly illuminating series of papers, Ramos-Fernandez and colleagues (2004) studied the foraging patterns of a group of free-ranging spider monkeys in the forest of the Yucatan Peninsula, Mexico, gathering a complete set of walk data on step lengths, waiting times, and turning angles. That the movement of these primates is consistent with a LW strategy is confirmed by both the power-law distribution of step lengths with a μ value of 1.7 and the super-diffusive rate of movement away from sleeping sites during the first foraging phase of the day. That waiting times also show power-law scaling suggests that spider monkeys feed on

resources that may be fractally distributed in both location and size. However, the turning angles, which are distributed around a marked peak at approximately 0, suggest that there is an element of correlation or bias in the foraging regime, leading the authors to conclude that what they have measured is not a "true" LW strategy.

A series of subsequent papers (Ramos-Fernandez et al. 2006; Boyer et al. 2006; Santos et al. 2007) elaborate on these findings, giving detailed consideration to the relationship between animal foraging and the structure of resources in the environment. It is important to note that Ramos-Fernandez and colleagues (2004) have found different step-length exponents for male and female monkeys, and also for lone individuals as opposed to those in groups. In particular, males have a larger proportion of long trajectories than females, indicating that the scale of their individual step-length distribution is extended so as to allow for their concomitantly larger day and home ranges (Ramos-Fernandez and Ayala-Orozco 2003). Monkeys foraging alone demonstrate a greater proportion of longer distances than those in groups, a discrepancy that the authors attribute to the greater chance of finding a patch of fruiting trees (and therefore travelling a series of shorter distances) when in a group.

The only substantive treatment of LW in an archaeological setting to date is provided by Brantingham (2006; see also Brantingham 2003) who has developed a formal model of forager mobility related to the transport and deposition of lithic materials and their recovery. This model is worth considering in some detail as it develops a novel series of potential behavioral implications arising from the adoption of Lévy-structured mobility that have clear archaeological correlates. By comparing the qualities of SRW and LW, Brantingham (2006:439ff.) suggests that the latter can be seen as an index of relative increases in planning depth, energy efficiency, and risk sensitivity. Planning depth is thought to increase due to the link between time and distance in LW as opposed to LF. As the possibility of large steps increases (i.e., as $\mu \to 1$), so the possibility of committing to the substantial period of time required to accomplish such longer steps also increases. As Brantingham explains, "if two foraging bases are separated by ten units of distance… then the forager must plan movement at least ten time steps in advance to ensure transit between bases" (Brantingham 2006:440). Energetic efficiency increases simply because the probability of travelling in a straight line between two resources separated by a distance greater than the (constant) step length of a SRW is higher under a LW strategy, and risk is reduced by the occasional long-distance movement away from a potentially depleted area in much the same way as initially suggested by Levandowsky and colleagues (1988a, b).

This model is applied via simulation to lithic transport data from 53 Châtelpérronian, Aurignacian, and Gravettian assemblages from the Aquitaine Basin with specific reference to the quantities of Bergerac chert transported from a known source area. Though the resultant exponent of $\mu = 0.86$ falls below the limit for Lévy behavior, it is strongly argued that a minimal number of as yet unrecovered longer distance chert movements could dramatically increase this estimate within the LW range. Furthermore, it is important that μ falls *below* the range describing LW foraging rather than above it, since the latter would imply a SRW and would therefore suggest that the system in question lacks those beneficial qualities attributed to LWs. Though he is right to advise caution, Brantingham is,

therefore, able to argue that "early Upper Paleolithic mobility in western France was both maximally planned and organized to minimize the costs associated with movement and exposure to risk" (2006:447).

Though Brantingham was the first archaeologist to appreciate the potential application of LW to archaeologically documented mobility, many archaeologists will be familiar with power laws and their spatial consequences in the context of the rank-size distribution and inferences made from it as to the emergence of socio-cultural organization (Hodder 1979; Pearson 1980; Johnson 1980, 1981; Adams and Jones 1997). Recent examples include Boyle's (1996) study of the potential socioeconomic interaction between Final Magdalenian sites in the Vézère Valley and the identification of subsystem settlement units in the spatial organization of Formative and Post-Classic Tiwanaku by McAndrews and colleagues (1997). The use of the distribution can be traced back even further in the human sciences more broadly, to Zipf's much-cited study of least-effort criteria (Zipf 1949). However, only recently have archaeologists begun to examine the more expansive implications of fractal distributions and their implications (Zubrow 1985 is a notable early anomaly). In particular, Brown (2001; Brown and Witschey 2003) has been instrumental in effecting what is in many ways simply a change in perception.

Lévy Walks in Hunter-Gatherers

Recognizing Lévy Mobility

With a broad theoretical and empirical basis established, this section briefly tackles the mathematics of identifying LW in empirical datasets. In order to demonstrate the various methods of LW identification, four of which are identified here, it is necessary to use simulated data that are drawn from a known distribution. This allows us to operate on a level playing field; the parameter values of the data distribution are known in advance (this is clearly not the case with animal movement data), and our task is simply to find the method that best reflects those values. For this reason, one million "step lengths," l, called from a Lévy distribution with $\mu = 2.5$, were simulated via the transformation method, given by $l = l_{min}(1-r)^{-1/\mu-1}$, where r is a uniformly distributed random variable $(r \in (0,1))$, and $l_{\min}$ is the minimum step length (this simulation follows Newman 2005). The minimum step length is necessary in theory because there will be a very small region of the abscissa, near the origin, for which predicted values of the power law will rapidly approach infinity. In empirical studies, the minimum step length is chosen as a behaviorally realistic "characteristic step length" specific to the study species in question; in the current analyses, it is set arbitrarily to $l_{min} = 1$.

Most graphical tests of LW involve plotting walk length l on the abscissa against the frequency of that walk length $f(l)$ on the ordinate. Equation 5.1 suggests the form plotted in Fig. 5.3a; however, taking natural logarithms of both sides of Eq. 5.1 gives:

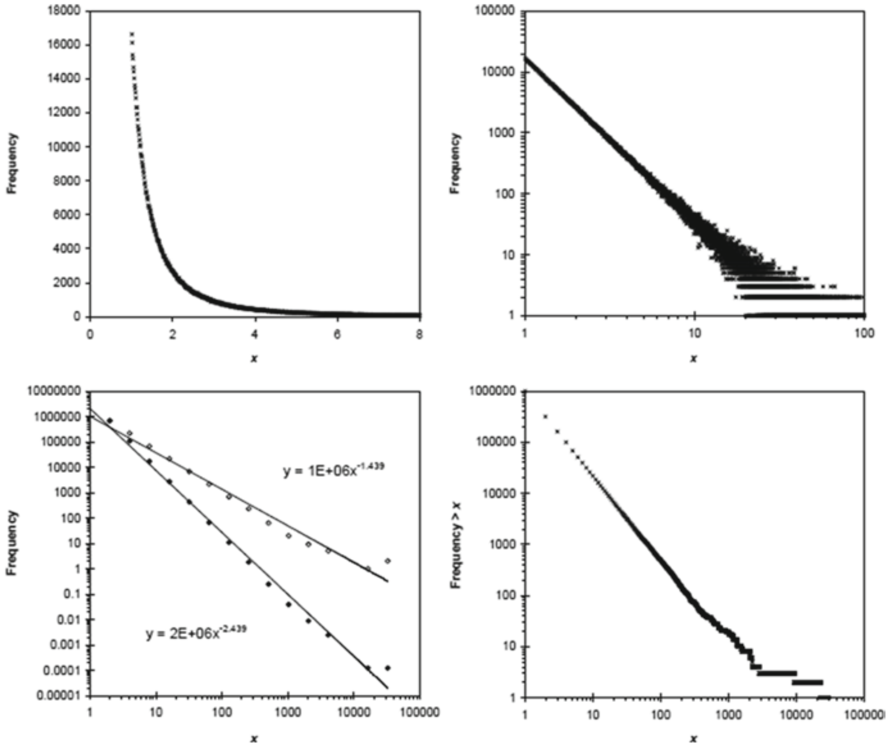

Fig. 5.3 Four graphical realizations of 1 million simulated steps of a Lévy walk. (**a**) *Top left*, a simple plot on linear scales, truncated at a maximum step length of eight units. (**b**) *Top right*, a similar plot on logarithmic scales truncated at 100 U; note the noise in the tail of the distribution. (**c**) *Bottom left*, two examples of "logarithmic binning." Only the *lower line* is normalized according to bin width; the *upper line* shows an incorrect exponent of $(1-\mu)$. (**d**) *Bottom right*, cumulative density or survival function

$$\ln\big(p(l)\big) = \ln c - \mu \ln l \tag{5.2}$$

This has the important implication that plotting a histogram of logged frequency per unit step length $\ln\big(f(l)\big)$ against logged step length $\ln(l)$ should result in a straight line with slope $-\mu$ in cases where power law behavior is present (see Fig. 5.3b).

Figures 5.3a and b represent what are in most cases the initial treatments of step-length data in ecological studies of mobility patterns. While there is a growing consensus that such graphs are not sufficient (e.g., Viswanathan et al. 1999; Benhamou 2007; Edwards et al. 2007; Sims et al. 2007), there is a routine failure to point out that they are in many ways necessary, both to characterize the data and to save potentially wasted time. Since these are the simplest ways of plotting step-length data, they can be considered in much the same way as the descriptive statistics generated at the start of any analysis.

Given that the simulated data do show power-law behavior, we may refine the analysis via two further plots. The additional plotting techniques involve the use of

variable bin widths, and need to be handled with care to avoid anomalous estimates of μ. To understand why variable bin widths are justified, consider the case in which, rather than simply plotting the raw data on log scales, we log-transform the data prior to drawing the graph. The transformed step-lengths then have a probability density function given by:

$$f(x) = \frac{\partial l}{\partial x} p(l) = c \exp\left(x\left(1-\mu\right)\right) \tag{5.3}$$

where $x = \ln(l)$. Taking logarithms of Eq. 5.3 gives:

$$\ln\left(f(x)\right) = \ln(c) + x\left(1-\mu\right) \tag{5.4}$$

This represents the case in which the data are transformed prior to plotting, and the bins used are of some fixed width *in the log-transformed variable*. As can be seen from Eq. 5.4, the slope of the graph in this case would be equal to $\left(1-\mu\right)$. The problem of the incorrect exponent arises because fixed bin widths of equal size in a log-transformed variable are not of equal size in terms of the original data. To take $\log_{10}$ transformation as the simplest example, the interval between 1 and 2 on the log scale represents the interval 1–10 in terms of the real data, whereas the interval between 2 and 3 on the log scale represents the interval 10–100 in terms of the real data. In this case, therefore, the second interval is ten times larger than the first, and so will contain ten times more data points on average, thus leading to an elevated line with an exponent of $1-\mu$. The solution to this problem is to divide the number of samples by the width of the bin into which they fall; normalizing the data in this way ensures that the line has a slope of $-\mu$. Examples of a line consistent with Eq. 5.4 and the normalized equivalent are shown in Fig. 5.3c.

The above described method, often referred to as "logarithmic binning," has the advantage of smoothing the variability found in the tail of the distribution (see Fig. 5.3b), and is favored by many researchers as a means of extracting the exponent (e.g., Viswanathan et al. 1999; Sims et al. 2007, 2008). However, there is one further method, favored by Newman (2005), involving a plot of the cumulative distribution function (CDF) of the data. Instead of plotting a simple histogram of the data, we make a plot of the probability $P(l)$ across the dataset that l has a value greater than or equal to l:

$$P(l) = \int_{l}^{\infty} \mathrm{p}(l')\, dl' \tag{5.5}$$

If the distribution follows a power law as per Eq. 5.1, then

$$P(l) = c \int_{l}^{\infty} l'^{-\mu} \mathrm{d}l' = \frac{c}{\mu - 1} l^{(1-\mu)} \tag{5.6}$$

Thus, this CDF also follows a power law with an exponent of $1-\mu$. Provided this is taken into account, however, the CDF is an accurate way of recovering the exponent. An example of a CDF plot is shown in Fig. 5.3d.

A Hunter-Gatherer Case Study

The previous section highlights the methods that can be applied to data to test for and characterize power-law behavior and, by extension, Lévy Walks. The current section puts some of those methods to the test by examining a dataset of hunter-gatherer camp relocation data collected by Yellen (1977). The data concern the rainy season camp movements of the Dobe area !Kung of north-eastern Botswana and north-western Namibia during the period January 27th to July 11th 1968, and comprise 37 movements that will serve as step lengths for the purposes of this investigation. These data are the most complete published account of hunter-gatherer relocation and as such are a prime resource for archaeologists and anthropologists seeking to model specific patterns of mobility (Grove 2008a, b). Following the generic discussion of random walks in "Lévy Walks," the complete set of walk characteristics for this data were calculated from a map and related table (Yellen 1977:66, Maps 7 and 60, Table 3, respectively) in the original publication. Camp locations, which stood for the points at which walk segments began and ended, were digitized, assuming that the center of each number on Yellen's Map 7 was equivalent to the center of the camp. Distances and turning angles were then calculated from the digitized map, with waiting times taken from the "number of days occupied" column in Yellen's Table 3. The total dataset is presented in Table 5.1.

Brown and colleagues (2007) have recently analyzed these data, suggesting that they conform to a LW with $\mu = 1.97$, remarkably close tothe $\mu = 2$ that Viswanathan and colleagues (1999) found to be optimal when searching for static, randomly distributed targets. They further argued that the waiting times were power-law distributed with an exponent $\mu = 1.45$, thus indicating the possibility that !Kung foraging behavior is fractal in both space and time. These conclusions, though important, were published before the papers of Sims and colleagues (2007) and Edwards and colleagues (2007), both of which highlighted the potential pitfalls discussed above. The following analyses thus reappraise and expand upon the research of Brown and colleagues (2007) in the light of these methodological advances, with a view to furthering the efforts to model hunter-gatherer foraging strategies. The following sections therefore deal with the step lengths, turning angles, and waiting times respectively.

Step Lengths

Brown and colleagues (2007:132) correctly note, with regard to bin size selection, that "narrow bins will be good estimators of short distances or times, but poor estimators of long ones, while the opposite will be true of wide bins." This issue is related to both the problem of noise in the tail of the distribution and to the need to ensure a sufficient number of bins with which to represent the sample. With regard to the latter, a sample size of only 36 sets strict limits on the creation of bins, as bin width will have a profound effect on the results. Brown and colleagues (2007) avoid this problem by

Table 5.1 The dataset used for the analyses of "Lévy Walks in Hunter-Gatherers." The sequence of camp numbers and waiting times were taken from Yellen (1977:60, Table 3), *x* and *y* coordinates were digitized from Yellen (1977:66, Map 7), and step lengths and turning angles were calculated from the digitized site locations. Turning angles are calculated relative to the previous segment, with degrees counted clockwise

Camp no.	*x*	*y*	Step length (km)	Turning angle (°)	Waiting time (days)
1 (Dobe)	17.174	0.781			
2	5.172	13.466	17.463	133.415	7
3	7.318	15.027	2.654	97.388	8
4 (2)	5.172	13.466	2.654	180.000	2
5	8.392	7.904	6.427	275.959	2
6	4.781	5.367	4.413	84.973	3
7	8.392	5.367	3.610	215.096	2
8 (1)	17.174	0.781	9.907	27.575	17
9	9.758	4.489	8.291	178.990	5
10	8.684	9.367	4.996	51.028	2
11 (2)	5.172	13.466	5.398	331.806	2
12 (3)	7.318	15.027	2.654	94.574	2
13	5.464	19.027	4.409	281.164	3
14	6.928	16.686	2.762	172.858	2
15	6.928	19.613	2.927	212.005	1
16	8.392	20.394	1.659	61.928	1
17 (14)	6.928	16.686	3.986	139.613	2
18	14.734	15.905	7.845	254.170	2
19 (1)	17.174	0.781	15.320	75.127	11
20	16.295	5.562	4.861	178.755	1
21	8.001	14.929	12.512	328.885	3
22	11.124	14.929	3.122	41.522	12
23	15.124	13.466	4.260	110.095	1
24 (1)	17.174	0.781	12.849	60.729	26
25 (9)	9.758	4.489	8.291	125.741	5
26	7.709	10.148	6.019	43.531	1
27	3.708	13.563	5.260	330.390	5
28	3.513	15.807	2.253	44.544	3
29	6.245	15.320	2.775	105.094	1
30	15.124	5.659	13.121	37.286	1
31 (1)	17.174	0.781	5.292	19.807	14
32	14.051	2.830	3.735	146.057	1
33	9.270	5.074	5.282	351.870	1
34	4.879	10.441	6.934	25.566	6
35	1.073	10.929	3.837	316.595	2
36	6.635	13.075	5.962	151.589	1
37	10.148	15.027	4.018	352.050	8
38 (1)	17.174	0.781	15.884	92.804	?

employing a methodology based on earlier work (Liebovitch et al. 1999, 2001) that combines probability density functions generated from histograms of various different bin sizes. This "multihistogram" method is described in detail in the appendix of

a paper examining cardiac rhythm abnormality (Liebovitch et al. 1999:3317–8), where it is clear that a fixed number of bins of each size are allowed to contribute to the composite PDF. Since it is the first *k* bins of each size (i.e., the *k* nearest the origin) that contribute to the PDF, larger bin sizes will necessarily cover a greater range of the sample; this has the property of reducing noise in the tail, but the cost in terms of lost data resolution is impossible to estimate. Since the precise application of this procedure (which is perfectly reasonable) to the !Kung data is not explained, the current paper employs the methods described above in the following reanalysis.

To account for the problem raised by Brown and colleagues (2007) with regard to choice of bin width, and to ensure that the current analyses are not in any way biased, the data were plotted separately according to a series of bin widths, a subset of which are presented visually in each case. Following the expedient procedure suggested above, geometric and logarithmic plots were produced initially and, where they demonstrated the potential for Lévy behavior, they were followed by plots based on logarithmic binning and CDF. The bin widths employed for the step-length data ranged from 0.1 to 4 km, with only the last returning a value for the resultant power law that was close to acceptable; this, however, was reliant on an unacceptably small number of bins (see Fig. 5.4). The conclusion, therefore, even at this early stage of analysis, is that the step lengths are not consistent with the Dobe !Kung performing LW between their camps.

Given this surprising result and bearing in mind the call of Viswanathan and colleagues (1999) for tests on distributions other than just that assumed a priori to be of relevance, the step length data were next subjected to a wider distribution-fitting strategy. Using the MathWave EasyFit program, a series of statistical and other distributions were fitted to the data, with the finding that the lognormal distribution provides the best approximation (Kolmogorov–Smirnov $P=0.96$). Furthermore, inspection of the original data and the description of it provided by Yellen (1977:62–3) demonstrates that, on three occasions, the group were transported by vehicle between bases. These “steps” were of 9.907, 7.845, and 15.320 km, respectively, and are therefore toward the longer end of the step-length range. Though it is impossible to assert that these journeys would not have been made by foot had a vehicle not been available, their removal from the sample weakens the fit of the LD but barely affects that of the lognormal (see Fig. 5.5).

Turning Angles

It was decided to test the turning angles of the Dobe !Kung data since they can inform on various features of the walk strategy. During the dry season the !Kung in this area are tied to the only permanent source of water available to them at the Dobe waterhole, to the south-east of their range. In the rainy season, from which these data arise, the subgroup followed made longer trips away from Dobe, though they returned to the waterhole on five occasions during the study period (Yellen 1977:54ff.). This suggests that the group might move in a looping pattern out from Dobe to forage, and thus that there might be a pattern of bias in their turning angles. The LW, like the SRW, predicts a random pattern of turning angles (i.e., they should

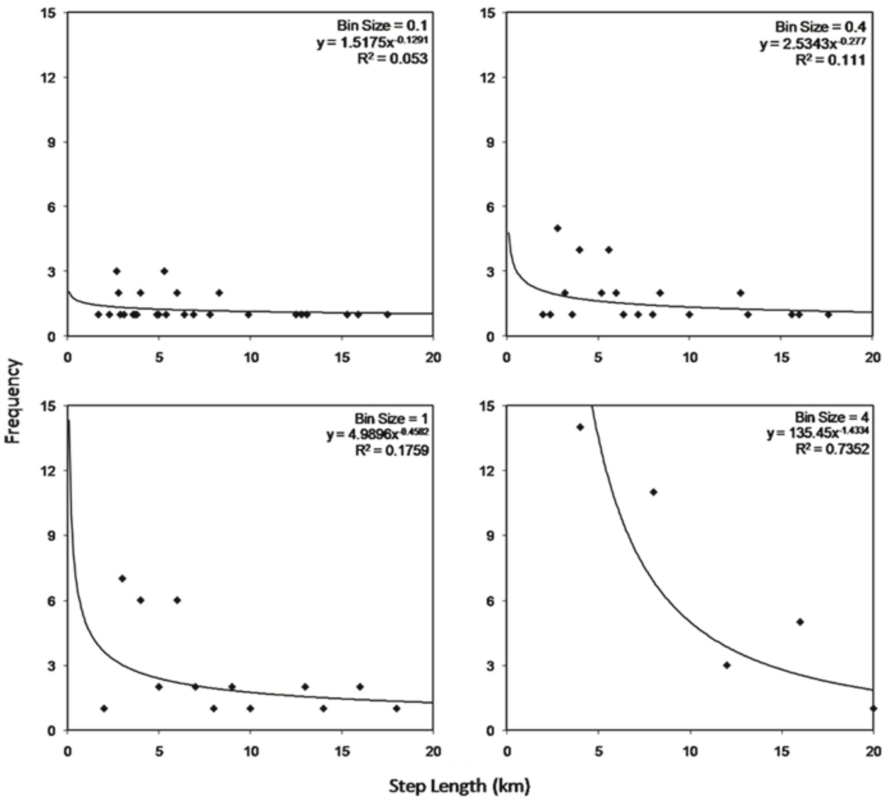

Fig. 5.4 Attempts to fit power laws to the Dobe !Kung step-length data with various bin sizes. None are significant

be distributed according to a circular uniform distribution), but other forms of walk such as the correlated and biased examples discussed above would predict normal distributions (in the short term) centered upon a preferred direction.

The bin widths employed for the turning-angle data ranged from 1° to 30°, with none supporting a distribution other than the circular uniform distribution. Generic distribution-fitting procedures using the EasyFit program confirmed this conclusion, which is consistent with the Dobe !Kung performing a walk that is not biased in any particular direction. This probably reflects the fact that, though the subgroup studied do clearly perform foraging trips that both begin and end at Dobe, their movements within each trip are effectively random. They do not describe a basic polygonal shape such as a hexagon, for example, where six (internal) angles of approximately 120° would bring the group back to the base and show a pronounced peak in the turning-angle graph. Instead, their movements are well dispersed, though Fig. 5.6 does show a slight, nonsignificant tendency toward the area of the graph <180°, suggesting that the group generally heads out to the west (equivalent to an initial bearing of 270°) before completing a broadly clockwise circuit and returning from the north.

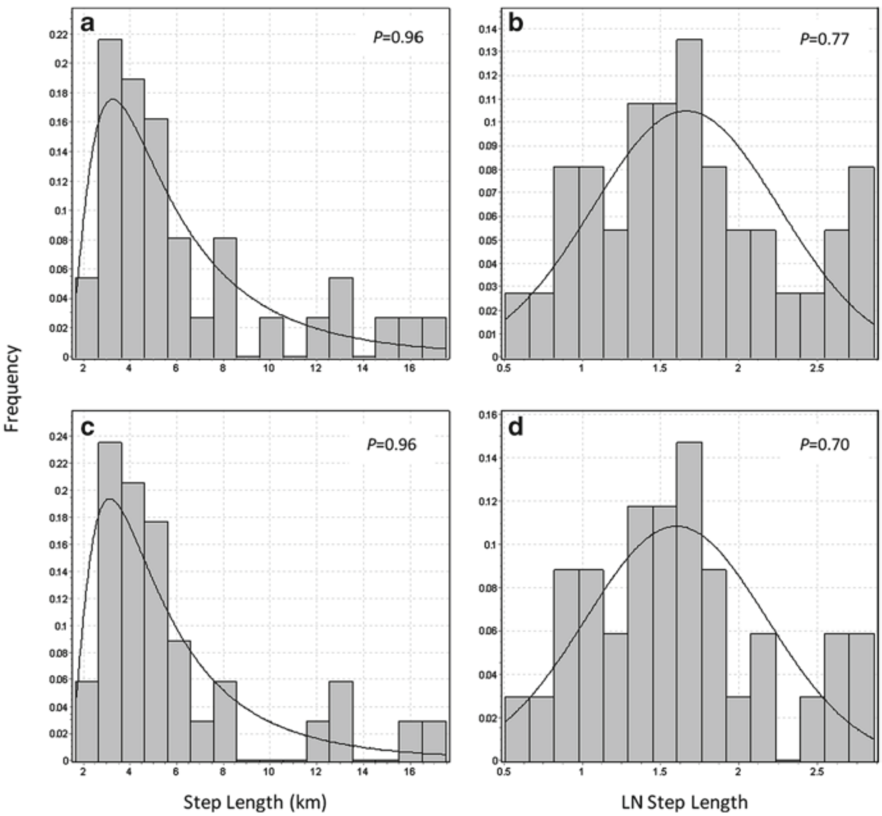

Fig. 5.5 (**a**) The complete Dobe !Kung step-length dataset and the lognormal curve that best approximates it. (**b**) The same data logged and fitted to a normal curve. (**c**) The dataset minus the trips made in Yellen's vehicle. (**d**) The data of (**c**) logged and fitted to a normal curve. Note the increase in the Kolmogorov–Smirnov *P* value when these trips are removed

Waiting Times

The waiting times are an important part of a walk's description, allowing us to infer patterns regarding the distribution of resources in the landscape. The temporal element of an LW is often ignored or treated as subordinate to a finding of power-law-distributed step lengths, but this is an unjustified bias. In the current circumstance, it is clear from "Step Lengths" that the !Kung do not conform to a LW, yet we can still infer patterns of interest about their foraging strategies and environment from the distribution of waiting times. The bin widths employed for the waiting time data ranged from 1 to 5 days, with all conforming to a power-law distribution. Figure 5.7a, b shows examples of these basic fits for bin widths of 2 and 3 days, respectively. Given the fact that power law behavior was detected in this scenario, plots employing logarithmic binning (LB) and CDF were also produced; they are shown here as Fig. 5.7c, d.

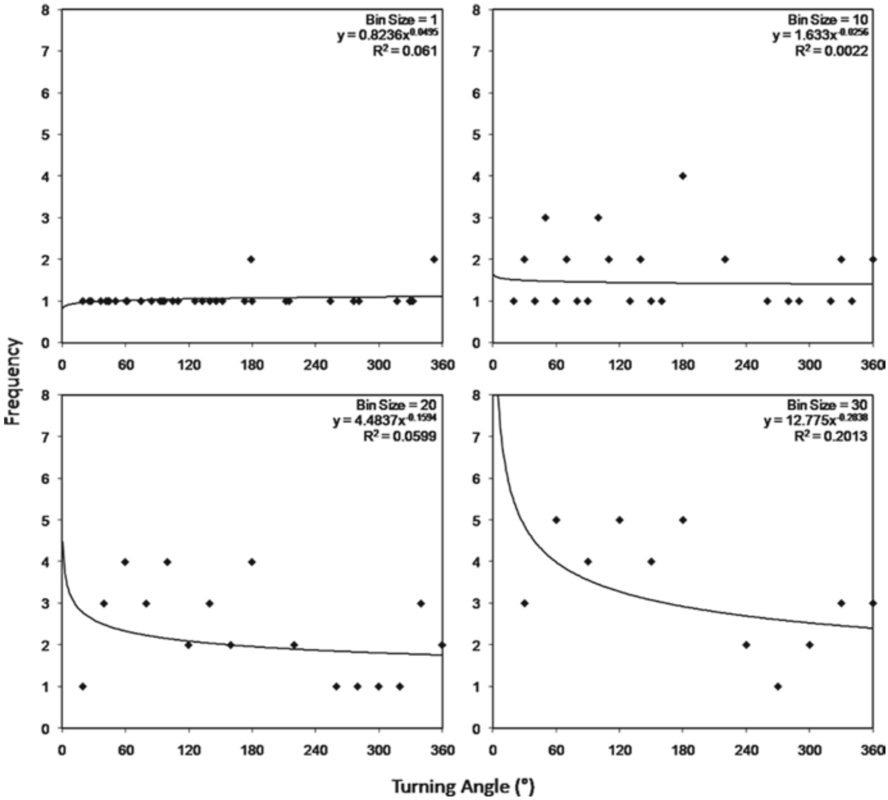

Fig. 5.6 The turning-angle data from the Dobe !Kung dataset. Power law fits are nonsignificant, with the data merely demonstrating a slight and nonsignificant tendency to group at angles <180°

This result provides a good example of the extent to which the exponent depends on the bin width when data are plotted on simple geometric and logarithmic graphs. Brown and colleagues (2007:133) found an exponent for the waiting-time data via their multihistogram approach of $\mu = 1.4503$, which is close to that found in the current analysis of 1.4968 based on a bin width of 3 days. However, the exponents found here based on 1- and 2-day bin widths are 0.8751 and 1.1652, respectively, while that for a bin width of 5 days is 1.9034. We thus have a range of variation of greater than one unit in the exponent due purely to the bin width chosen; though this seems a small amount, it is in fact very high relative to the LW range of $1 < \mu < 3$. The LB and CDF plots offer a greater measure of agreement as to the exponent, with the normalized LB plot giving a value of 1.506 (the nonnormalized plot gives 0.506) and the CDF, when appropriately adjusted, giving 1.453. This latter figure is remarkably close to the 1.4503 reported by Brown and colleagues (2007:133).

The use of the LB and CDF plots raises the issue of choosing an appropriate value of $l_{\min}$. Figure 5.7c, d was produced with $l_{\min} = 2$, meaning that the first bin (that nearest the origin) was ignored in both cases. The selection of an $l_{\min}$ value

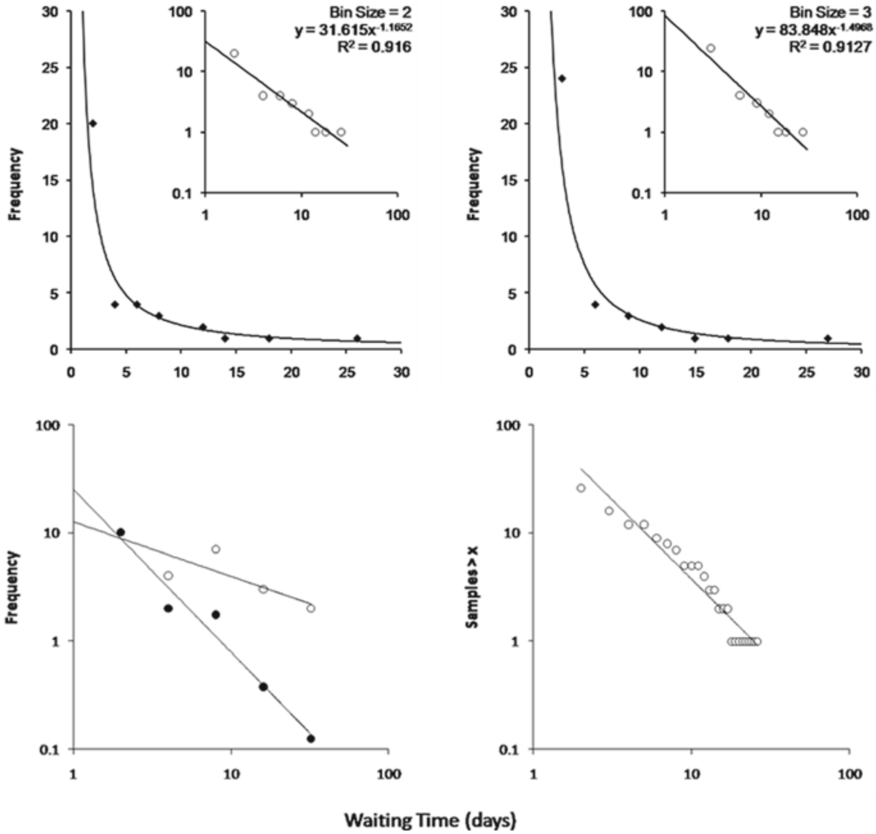

Fig. 5.7 The Dobe !Kung waiting-time data conforms to a Lévy distribution for bin sizes of two and three (*top left* and *right*, respectively). The figure *bottom left* shows an example of logarithmic binning with a nonnormalized exponent (*white circles*, $\mu = 0.506$) and a normalized exponent (*black circles*, $\mu = 1.506$). The figure *bottom right* shows a cumulative density function with a normalized exponent of $\mu = 1.453$

greater than the smallest value in the dataset necessarily means that not all the data is utilized in drawing the power law, and therefore that the exponent reflects only the data with values $l \geq l_{\min}$. This is standard practice in ecological mobility studies, and indeed in the fitting of power laws more generally (Newman 2005), but raises the issue of how best to predict the lower limit of power law activity. In practice, there are few available guidelines, and $l_{\min}$ is generally chosen by eye, but it should be noted that the value chosen can affect the exponent considerably. As an example, a CDF of the waiting times data with $l_{\min} = 3$ yields an exponent of 1.539, while setting $l_{\min} = 4$ gives 1.641; these differ considerably from the figure of 1.453 returned in Fig. 5.7d. Nor is this problem confined to graphical solutions; a widely used analytical solution for extracting the exponent is given as follows:

$$\mu = 1 + n\left[\sum_{i=1}^{n} \ln \frac{l_i}{l_{\min}}\right]^{-1} \tag{5.7}$$

where $l_i, i = 1 \ldots n$ are the waiting times, n being the sample size. For the waiting-time data, this equation yields μ values of 1.956 for $l_{\min} = 1$ and a remarkable 3.823 for $l_{\min} = 2$. Rearranging and solving for $l_{\min}$ yields a value of 0.313 for $\mu = 1.453$, a minimum step length considerably below the resolution of the dataset.

The variety in these estimates, for both graphical and analytical solutions, is largely because of the sample size available for these analyses. Not only is the initial sample size small, but it is reduced further when the value of $l_{\min}$ is chosen to be greater than the minimum measurement in the sample. For this reason, it is clear that the CDF is the best graphical solution for small datasets, since it utilizes all the available data greater than $l_{\min}$, employing 25 data points to derive an equation as opposed to the 5 employed by the LB method for this dataset. For this reason, the exponent of $\mu = 1.453$ produced via the CDF plot with $l_{min} = 2$ is considered to be the most reliable characterization of the waiting time dataset. The waiting times, therefore, demonstrate power-law scaling within the value prescribed for Lévy behavior.

The Dobe !Kung Foraging Strategy

When drawing the results of the previous three sections together, we arrive at a picture of a foraging strategy in which turning angles are basically random, but with a slight clockwise looping tendency, step lengths are lognormally distributed, and waiting times conform to a Lévy distribution. This allows us to make a series of inferences about the nature of Dobe !Kung mobility and to speculate about the interactions between these foragers and their environment. The current section, therefore, examines each of the elements of the foraging pattern in turn and attempts, where possible, to relate these to earlier archaeological models of hunter-gatherer mobility.

The turning angles are treated first, since they offer the least informative results, and do not allow us to differentiate with any confidence between the models introduced in "Lévy Walks"; however, it should be noted that the walk strategy of a forager is only ever a composite of these three elements and that a single variable will never accurately describe the full nature of the walk. The turning-angle data highlight what might be seen as a weakness of this form of analysis; it is impossible to force a SRW and a LW into a situation of mutually exclusive predictions with regard to the turning angles alone. Although it would be naïve to expect human foragers to conform consistently to a narrowly prescribed strategy, the finding of randomness in the turning angles allows us only to rule out any element of correlation or bias in the paths of Dobe !Kung foragers. This could suggest either of two possibilities: the !Kung forage without prior information and expect resources to be randomly distributed or they have established via direct or socially mediated information gathering prior to departure the locations of the necessary resources, and these resources are in fact randomly distributed. The extent to which information levels effect RW models and foraging more generally is addressed below in "Discussion."

That the waiting times are Lévy-distributed allows us to speculate as to the size of the resource patches available to the group and, in conjunction with a finding that the

step lengths are not Lévy-distributed, points to a series of interesting possibilities. Firstly, the default assumption regarding LW, when the step lengths are scale-free, is that resources are fractally distributed (e.g., Marell et al. 2002; Bartumeus et al. 2003; de Knegt et al. 2007) although, as Viswanathan and colleagues (1999, 2000) have made clear, a LW also offers advantages in environments where resources are distributed at random. The assumption given the result of lognormally distributed step lengths is that resources are not fractally distributed, and that the distances between patches are far more regular than would be found in a fractal environment. To see this difference, compare the simulations of Lévy and lognormal walks shown in Fig. 5.8. Effectively, the nested quality of a scale-free structure in which similar patterns repeat across scales from the small to the very large is absent in the environment of the Dobe !Kung, and this could be due to a number of reasons. First, the environment in which the !Kung of this area operate is very rich relative to those of many other hunter-gatherer groups (see Kelly 1983, 1992, 1995; Binford 2001), and this may limit the need for long-distance relocations. Second, the specific group followed by

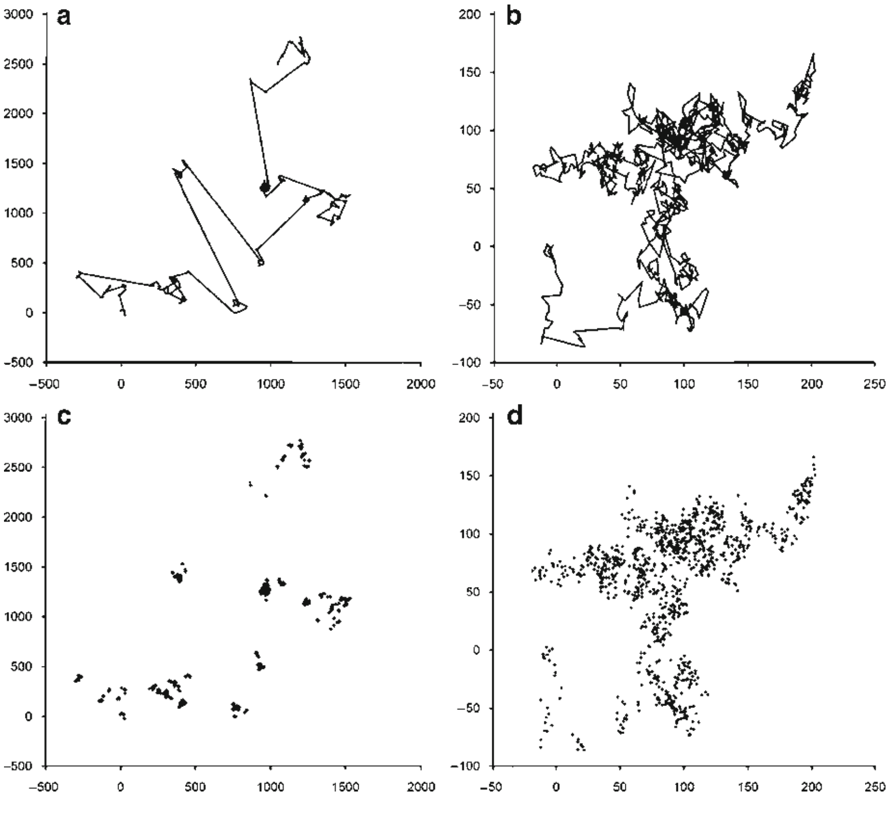

Fig. 5.8 (**a**) and (**b**) Show 1,000 simulated steps each of a Lévy and a lognormal walk, respectively. (**c**) and (**d**) Show those walks reduced to "dusts" by the removal of the walk vertices; the lower figures are representative of the most that could remain in the archaeological record as evidence of prehistoric foraging activities

Yellen were only a subgroup of the Dobe area !Kung, who were themselves only a subgroup of the wider !Kung population that extended further south into Botswana and Namibia as well as north into Angola. Thus, there may have been spatial issues related to the occupation and depletion of adjoining areas by neighboring groups. Yellen (1976, 1977; see also Howell 1976, 1979; Lee 1976) highlights the fluidity of the population located in the Dobe-/du/da region, and stresses the reliance on distant kin in times of resource scarcity. It is easy to see, therefore, how the wider population could both constrain (via competition) and expand (via cooperation) the resource base available to a particular small band without their having to travel very long distances on a regular basis. Finally, though the rainy season allows this band more freedom to move than they would have during the dry months, they are still restricted by a limited number of temporary standing water sources during their foraging round. This could curtail the distances they are able to travel, particularly if longer distances involve travelling into territory where water sources are not known.

Fractal scaling is absent, then, in the distribution of resources visited by the !Kung, but one can infer a fractal distribution in the *size* of the patches they visit from the waiting times. This inference, however, needs to be tested formally with data on the resource structure of the Dobe environment. It is now generally recognized that waiting times correspond broadly to the "handling times" referred to in the optimal foraging literature (e.g., Stephens and Krebs 1986; Houston and McNamara 1999) and that we can, therefore, extrapolate from waiting times to patch size. This is perfectly simple when the patches sought by the !Kung are plant resources such as mongongo nuts but can also be applied to game such as the duiker or gemsbok hunted by this group (see Burger et al. 2005). The finding of Lévy-distributed waiting times, therefore, suggests that although the patches are never too far apart, they are arranged in a way such that there is a large probability of encountering a small patch but a small probability of encountering a large patch. We might even extent this finding to suggest that plant foods are plentiful, but large game are rare.

Finally, another feature of the lognormal distribution that marks it out from the LD is that it predicts a negligible number of short steps (see Fig. 5.9); the LD, by contrast, predicts that the majority of steps will be very small. Figure 5.9b clearly shows that while the discrepancies between the two models and the data are similar and small for step lengths >6 km, the lognormal provides a much better fit for step lengths of <5 km. This is simply because the lognormal predicts correctly the very small number of moves of this distance. While there have been numerous theoretical and empirical findings in favor of LW as a search tactic, it is clear that in the case of the Dobe !Kung it is incapable of explaining the empirical data; on further reflection, we might suggest a simple theoretical explanation of why this should be so.

Human foragers, as per many other animals, will tend to deplete the resources in the vicinity of an occupation site to a degree proportional to the period of occupation; as such, it makes little sense to move only a short distance to the next site after an initial period of any substantive length. Any animal that does so would risk resuming a search in an area that it had previously depleted. In fact, this basic logic accords well with one of the simplest and most useful series of mobility patterning models to emerge from anthropology.

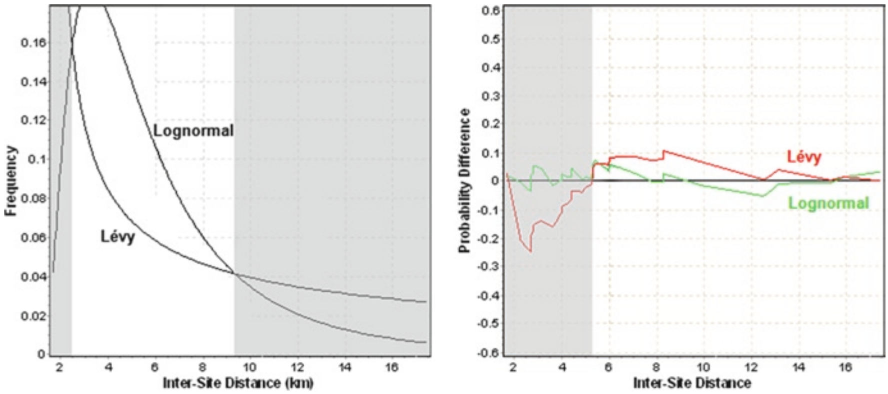

Fig. 5.9 A comparison of the best-fit Lévy and lognormal curves for the Dobe !Kung step-length data. *Shaded regions* are those in which the lognormal predicts fewer step lengths than the Lévy. These include, crucially, the *area of the graph* on the *left* corresponding to step lengths of ≈2.5 km and under. The *graph* to the *right* shows the probability that the fitted distributions differ from the actual data across the range of step lengths. It is clear that whilst the lognormal is only a marginally better fit for longer step lengths, it is considerably better for shorter step lengths

Binford (1982), in a seminal paper on hunter-gatherer spatial organization, outlines three patterns of camp movement that depend on a combination of mobility strategies and the underlying natural resource base. Initially, a distinction is drawn between the foraging radius and the logistical radius around a given site. The former corresponds to the area searched and exploited by "work parties" that return to the central site each night, while the latter refers to a zone which is "exploited by task groups who stay away from the residential camp at least one night before returning" (Binford 1982:7). By this definition, the group followed by Yellen were a task group exploiting the logistical range, a categorization that has important implications when we come to examine Binford's ideas about camp relocation. Figure 5.10 shows Binford's three models in schematic form. They are:

1. The *half-radius continuous pattern*, a high mobility pattern in which the group covers a broadly semi-circular foraging range before relocating to the outer edge of that range.
2. The *complete radius leapfrog pattern*, in which a group exploits a circular foraging range before moving approximately twice the radius of that range.
3. The *point-to-point pattern*, in which a group exploits a circular foraging area around a central site before moving well outside even the logistical area surrounding that site.

These patterns were established following Binford's studies of the Nunamiut (Binford 1978a, b, 1980) but accord with earlier developments concerning foraging radii around archaeological sites (e.g., Vita-Finzi and Higgs 1970; Higgs and Vita-Finzi 1972). The half-radius continuous pattern, in fact, owes its genesis to data gathered by Yellen on specific trips made by the Dobe !Kung (Binford 1982:9; 1980:7–9), though the data dealt with in the current paper more closely resemble the complete radius leapfrog pattern.

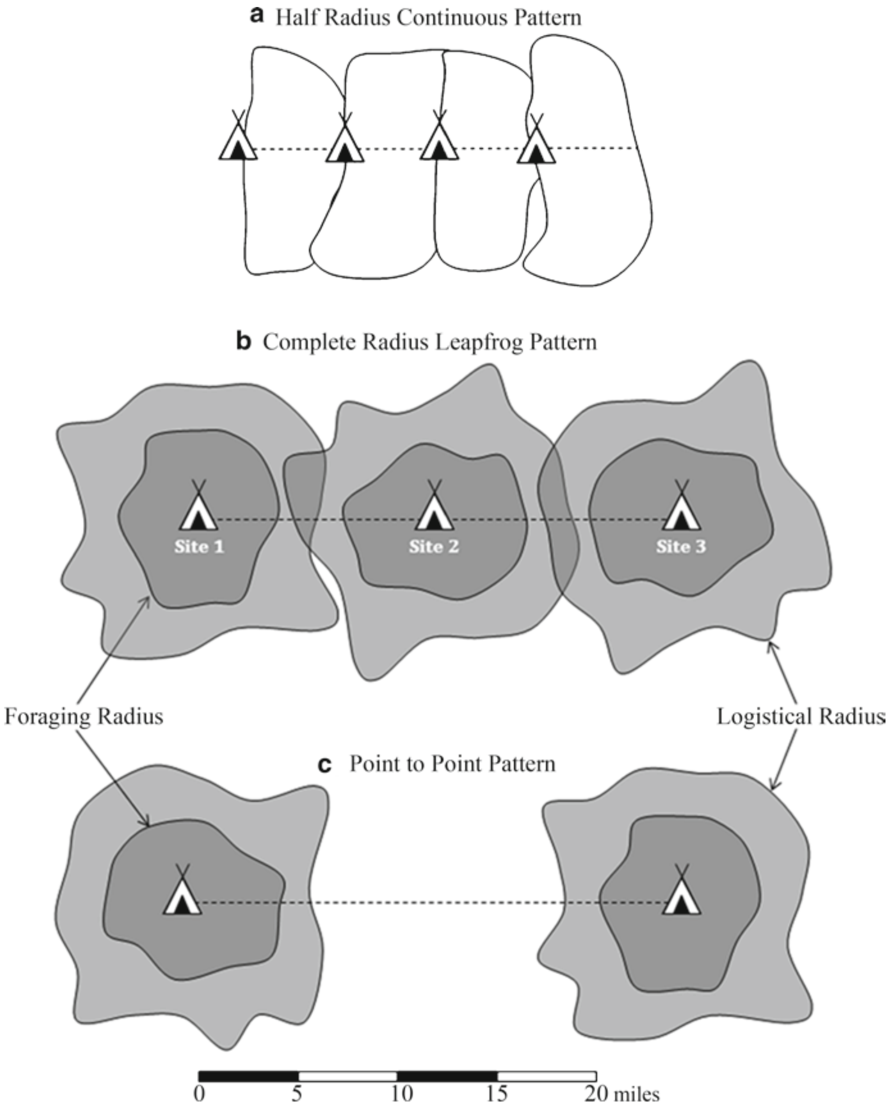

Fig. 5.10 Binford's (1982) series of idealized camp movement patterns in schematic form. Redrawn after Binford (1982:10, Fig. 2). For further details, see "The Dobe !Kung Foraging Strategy"

Binford's (1982) theoretical models illustrate the idea, put forward above, that short moves are of very little value to a hunter-gatherer group that has been foraging in a given area for any nontrivial period. In addition, he suggests that the complete radius leapfrog pattern is characteristic of foragers in high-biomass environments, while the point-to-point pattern is of more use in low-biomass areas. We might logically translate this difference into the suggestion that a group would relocate further in a low resource environment, since the area locally exploited from any

given site would be wider, and the possibility of having to traverse barren areas would be higher (Grove 2009). This seems sufficient to account for the relatively low variability in Dobe !Kung step lengths, and it could be suggested that what variability exists represents an environmentally cued strategy of moving back and forth along the continuum from half-radius continuous to point-to-point movement.

Archaeological Extensions and Implications

While the above sections have dealt with some of the basic ecological questions arising from the techniques and results discussed in the current paper, the following two sections attempt to provide links between those broad questions and the more specific aims of the archaeologist. The differences fall into two distinct categories; first, as archaeologists, our explanations tend to deal explicitly with hypotheses about human social or cognitive evolution and, second, the data available to us are rather different in form.

Archaeological Explanation

The theoretical models encountered above omit many factors that should ideally be addressed in archaeological discussions. In particular, the role of social networks in mediating environmental knowledge – and hence likely foraging strategy – is a prominent area of study in both anthropology and archaeology (e.g., Kelly 1995; Gamble 1998; Whallon 2006). It might further be considered that the maintenance of such networks is a fundamental part of what is a *social* adaptation to uncertain environments (Gamble 1983). As Whallon (2006:260) has stated, “the ethnographic record is full of examples of people moving, individually and in groups, for reasons of social contact…quite separate from subsistence pursuits.” Such movements appear to be part of a long-term strategy mediating against local ecological catastrophe. An obvious application of methods designed to characterize scale-free systems of the kind found by Brown and colleagues in a number of archaeological datasets (Brown and Witschey 2003; Brown et al. 2005) would be the study of the relationship between social organization and spatial organization, as both show clear fractal properties (Zhou et al. 2005; Hamilton et al. 2007). The issue of social organization also has a strong bearing on the advanced cognitive abilities that many would consider to provide a division between humans (or hominins) and other animals, a key difference involving the extended spatial and temporal scales over which social relations are maintained in humans (Rodseth et al. 1991; Gamble 1998, 1999). That human cognitive evolution has taken place in an explicitly social context (Grove and Coward 2008), and that that context appears to have been continually expanding in geographic scope (Grove 2010) needs to be taken in to account as we attempt to construct models of prehistoric forager mobility.

Modeling Archaeological Walks

The analyses detailed above accurately quantify the movement pattern of a Dobe area !Kung foraging band; however, it is only via Yellen's (1977) detailed recovery of data encompassing the entire foraging round that these analyses are possible. Such data are rare in anthropology, while prehistoric archaeologists face an even greater inferential gap between the methods pioneered in ecological studies and those required to extract movement data from the site-based record. Arguments concerning exactly how different humans may be from other animals, when these differences first appeared, and how much they matter are perpetual and in many ways unimportant; what matters at a more pragmatic level is the fact that our data are very different to those of ecologists. Australopithecine radio telemetry data are beyond our reach, and the reconstruction of movement patterns of extinct species or even ancestral *Homo sapiens* from their archaeological remains adds a rather cumbersome layer of complexity to a research strategy which, as emphasized in "Lévy Walks in Hunter-Gatherers," already has its problems. Gamble (1998:441; see also Gamble 1996) has argued that "the locales and paths, rather than the surface-area territories which surround them, are the important elements in the foragers' socially constructed landscapes," yet the development of methodological approaches to recovering such paths is a neglected field. In a rare archaeological treatment, Gibson (2007) highlights the importance of treating paths as elements of material culture, and demonstrates how their use and maintenance reflect changes in regional settlement patterns. For the most part, however, the paths that prehistorians study will no longer be visible and must be inferred from the remaining sites.

Fortunately, however, the general framework of RW studies in the physical sciences can be adapted to deal with the kinds of data that archaeologists routinely uncover. The current section therefore provides a brief summary of an ongoing research program into the relationship between archaeological sites and the paths that once connected them. This research is based upon the idea of the "Lévy dust," studied extensively by Mandelbrot and others (Mandelbrot 1983; Ogata and Katsura 1991). A dust in this sense is simply a series of points representing the turning locations of a LW; indeed, any random walk may be reduced to a dust of nodes merely by removing the vertices of the walk. The logic adopted here is that any series of contemporaneous archaeological sites were at some point connected by a series of paths (now lost) and that these paths can be approximated by some form of RW. While we cannot recover the paths themselves, we can simulate a series of random walks, based upon multiple working hypotheses about forager movement patterns that produce dusts that can be compared with the patterns of lithics and other materials found in the archaeological record. Such patterns are characterized not by the paths themselves (since we have no way of knowing which sites were connected to which others in archaeological contexts) but by the complete distribution of intersite distances available in the sample. That is, for both the archaeological and theoretical "dusts," the distance from each site to every other is measured, and the resulting intersite distance distributions (IDDs) plotted. Formally, for a given random sample

$X_1,\ldots,X_n$ of archaeological sites, the empirical density function is calculated for a given distance d as:

$$f(d)=\frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n} I\left(\left(d-b\right)<\left(X_i,X_j\right)\leq d\right) \tag{5.8}$$

where b is bin width and $I(\cdot)$ is an indicator function that takes the value 1 if the succeeding constraint is satisfied, and 0 otherwise. In this case, using !Kung camp locations as a proxy for archaeological sites, the IDDs were calculated by applying Eq. 5.8 to the Dobe intersite distance data directly, and to simulated scatters of archaeological material produced via both Lévy and lognormal walks. Lévy-distributed step lengths were simulated using the transformation method, $l=l_{\min}\left(1-r\right)^{-1/\mu-1}$, where r is a uniformly distributed random variable $\left(r\in\left(0,1\right)\right)$ (Newman 2005; Press et al. 2007). The exponent of the power-law distribution was set to $\mu=1.9675$, the result obtained by Brown and colleagues for the Dobe step-length data (Brown et al. 2007:133). Lognormally distributed step lengths, from the two parameter lognormal distribution,

$$f(d)=\frac{\exp\left(-\frac{1}{2}\left(\frac{\ln d-\mu}{\sigma}\right)^2\right)}{d\sigma\sqrt{2\pi}}, \tag{5.9}$$

were simulated via the LognormalRand function supplied with the EasyFit software (MathWave Inc.). From the analyses presented in "Lévy Walks in Hunter-Gatherers," the empirically derived parameter values for the Dobe data are are $\sigma=0.5889$ and $\mu=1.6613$. By comparing the IDDs of the Dobe data with those of both the Lévy and lognormal simulations, the data can be matched to the simulated walk most likely to have generated it. The simulation results are presented for the Lévy distribution in Fig. 5.11, and for the lognormal distribution in Fig. 5.12. Both are composed of 37 step walks, yielding 38 "sites" (the number of sites in the Dobe sample) and are replicated 1,000 times with each walk beginning at the same origin; the graphs in Figs. 5.11d and 5.12d show the averages over these combined replications.

Figure 5.13 compares the results of the simulated IDDs with the IDD produced directly from the Dobe step length sample. Though there is no established metric with which to compare the fit of the two distributions, it can at least be stated that the average residual between the frequency predicted by the Lévy walk simulation and that occurring in the data distribution is 14.53 units, while that between the lognormal simulation and the data is only 6.77 units. Furthermore, it is perfectly clear from Fig. 5.13 that the lognormal offers a far better approximation of the data than does the Lévy. The importance of this result is twofold. First, given that the Dobe data were shown above to be best characterized by a lognormal distribution of step lengths, the finding that an IDD generated via a lognormal walk closely resembles that generated via the data demonstrates the efficacy of the IDD method. Second, and more importantly for future archaeological applications, the IDD

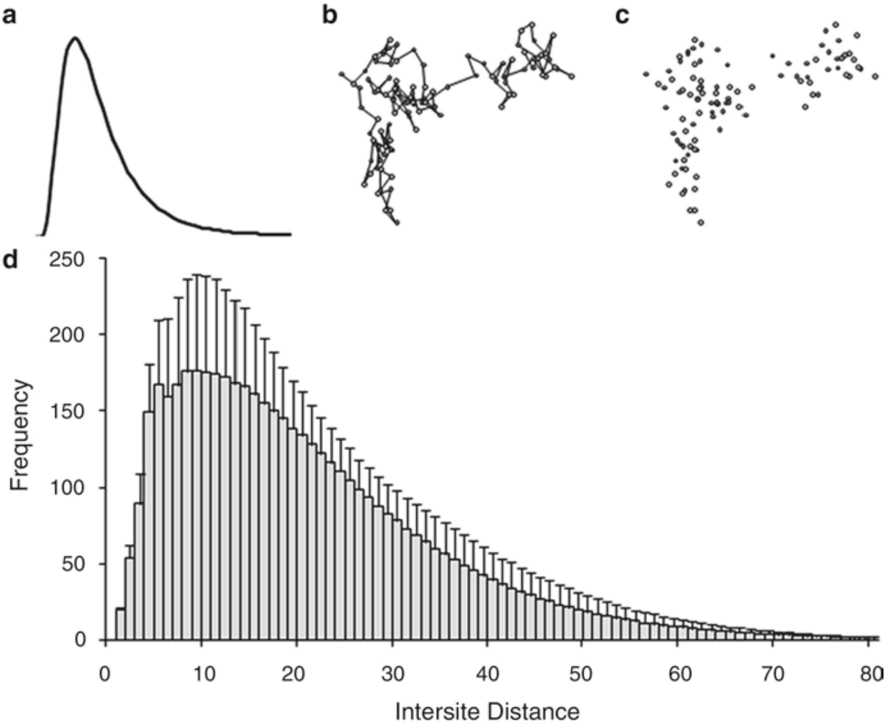

Fig. 5.11 The method employed for simulating multiple lognormal walks. (**a**) Shows the generating distribution, a lognormal distribution with σ=0.5889 and μ=1.6613, used to generate 1,000 walks, one of which is shown in (**b**). (**c**) Shows the dust resulting from the walk shown in (**b**); this is achieved by simply removing the vertices of (**b**), thus leaving the "sites" established at the turning points of the walk. (**d**) Shows the intersite distance distribution, averaged over 1,000 replications, that results from this walk pattern. The *error bars* in (**d**) are standard errors of the mean calculated for each one unit distance of the distribution

method allows us to characterize movement patterns from lithic distributions for which the actual step-length distributions cannot be recovered. This technique, therefore, provides a bridge with which to traverse the inferential gap between modern ecological random walk analyses and the application of similar analyses to the lithic scatters most often encountered in the archaeological record.

The application of this method to archaeological data relies only upon the need to establish the contemporaneity (within appropriate dating limits) of the sites to be included in the sample. That is, the temporal window within which the sample falls should not exceed the expected duration of a given band. While the exact limits of this window are currently unclear and require further research to establish, one can immediately see that establishing relative contemporaneity will be a simpler task in historic and recent prehistoric periods than it will be in the Paleolithic. This is an unfortunate limitation, and one that might be addressed by stochastic modeling incorporating the error intervals associated with various dating methods. A further apparent limitation is that the simulations assume all sites in a sample were created

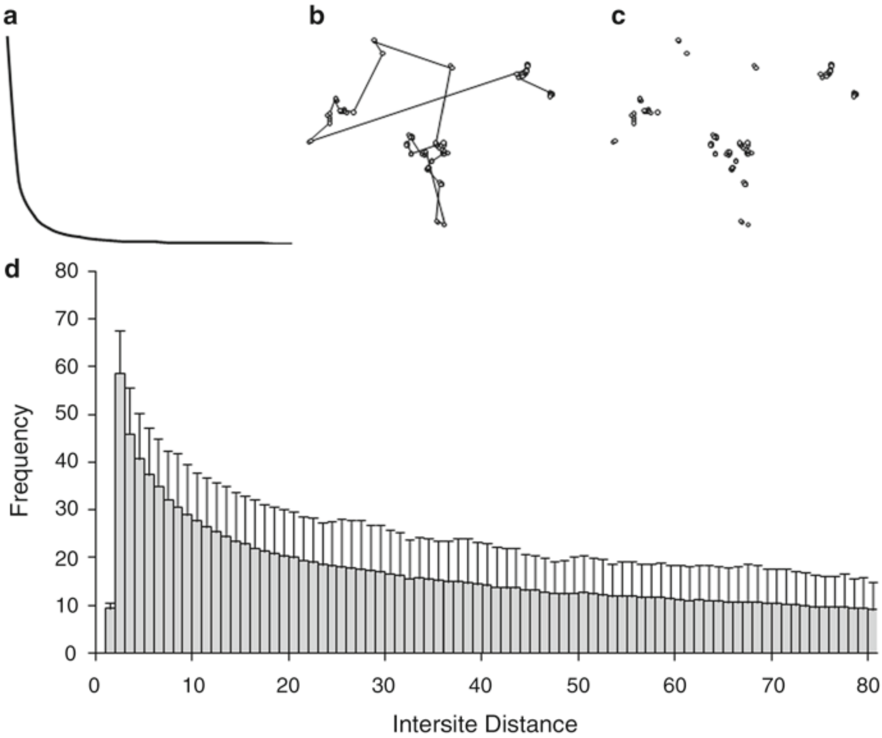

Fig. 5.12 The method employed for simulating multiple Lévy walks. (**a**) Shows the generating distribution, a Lévy distribution with $\mu = 1.9675$, used to generate 1,000 walks, one of which is shown in (**b**). (**c**) Shows the dust resulting from the walk shown in (**b**). (**d**) Shows the intersite distance distribution, averaged over 1,000 replications, that results from this walk pattern. The *error bars* in (**d**) are standard errors of the mean calculated for each one unit distance of the distribution

by the continuous movement pattern of a single band. In practice, however, the problem of multiple bands overlapping in a given area is dealt with via the existing simulation protocol. In mathematical terms, the replication of 1,000 walks by a single band is equivalent to, for example, 250 walks by each of four bands. As a verification of such equivalence, the above simulations were repeated with the origin of each walk occurring at a randomly chosen site created by the previous walk; this alteration is considered more appropriate to the modeling of multiple bands and has no effect on the average IDD curves, though it extends the standard error for a given d by between 0 and 19%.

Discussion

The above method extends the application of random walk analyses to archaeological datasets; however, there remain a number of debates around such methods that archaeologists should be aware of while engaging in analyses of this kind.

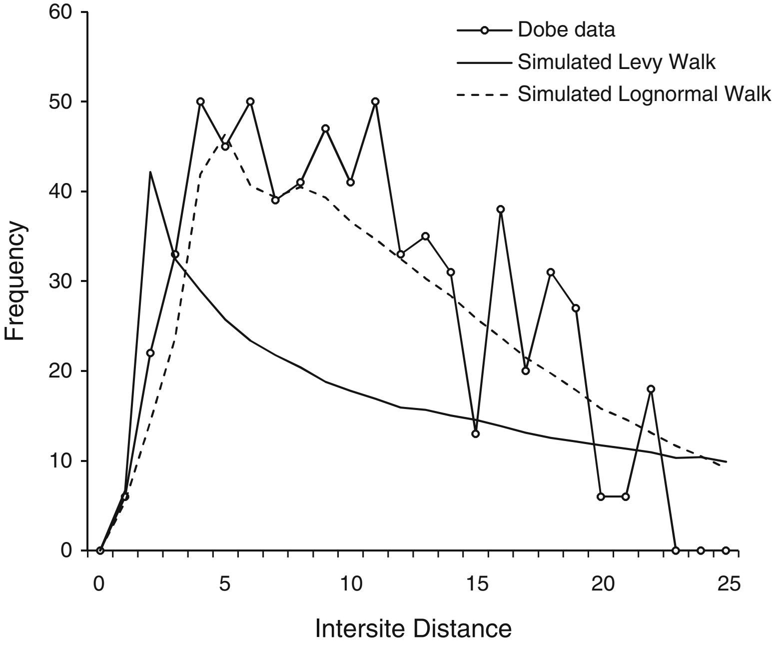

Fig. 5.13 Simulated Lévy and lognormal walk intersite distance distributions plotted against the intersite distance distribution from Dobe. It can be seen from this figure that the lognormal IDD provides are far better fit to the data than that of the Lévy walk

Scale-Free; or Multiscaled?

While the possibility of scale-free search patterns has created considerable excitement, a number of recent papers have suggested a promising alternative explanation for these apparent power-law patterns (Gautestad and Mysterud 1993, 1995, 2005, 2006; Gautestad et al. 1998; Morales et al. 2004; Benhamou 2007; Benichou et al. 2007; Zhang et al. 2007). The alternative explanation is based on the idea that animals switch between search modes as they enter different regions of their environments. If the strategy is not consistent during the period over which the walk is analyzed, the data should be divided into behavioral "bouts" that correspond to these modes. Morales and colleagues (2004) give the example of an animal performing a search alternately in resource rich and resource poor areas. They suggest that in the resource-rich area, "the animal's step lengths will be short, turns will be frequent, and turning angles large," while in the resource-poor area, the animal will revert to an "extensive search" strategy with "longer step lengths and small, infrequent turning angles" (Morales et al. 2004:2436). This two-stage model provides a good fit to the elk relocation data studied by these authors. In a similar vein, by altering the ratio of the means and the proportion of steps chosen from two independent exponential distributions, one intended to represent

intrapatch movement and the other interpatch movement, Benhamou (2007:1963ff.) was able to arrive at a step length distribution that would have passed the most rigorous statistical tests of LW behavior. It is possible therefore that multiple scale-specific behaviors are being lost within over-arching, scale-free curves.

Morales and colleagues (2004:2444) conclude that "describing movement paths in heterogeneous environments and over longer time scales for large cognitive animals will require more sophisticated models that account for greater behavioral complexity." One such model, developed by Gautestad and Mysterud, encompasses site fidelity and other memory-dependent behaviors in a "multi-scaled random walk" (MRW). Here an animal responds to an internal cognitive map of the environment as well as real-time interactions with the external world (Gautestad and Mysterud 2005, 2006). This model, like that of Benhamou (2007), can lead to fractal patterns of movement and has been supported by data from sheep and black bears (Gautestad and Mysterud 1993; Gautestad et al. 1998) as well as an extensive meta-analysis of animal relocation data (Gautestad and Mysterud 1995).

Evolved and Innate; or Intelligent and Reactive?

A recurrent theme of recent models that move beyond the fitting of simple distributions is the desire to situate the animal as a reactive agent in a dynamic environment. What varies among these approaches, however, is the extent to which the environment is thought to determine behavior. A particularly illuminating series of papers on this issue have examined foraging activities of a species of spider monkey, *Ateles geoffroyi*, via both empirical and simulation studies. As discussed in "Lévy Walks," Ramos-Fernandez and colleagues (2004) were able to demonstrate LW behavior in a group of these monkeys; following earlier theoretical work on LW (e.g., Viswanathan et al. 1999, 2000) it was considered that this might be an evolved strategy for the efficient location of randomly distributed resources (see also Bartumeus 2007). However, recent studies by this team have argued convincingly for an underlying environmental influence on foraging activity in spider monkeys (Ramos-Fernandez et al. 2006; Boyer et al. 2006). Boyer and colleagues (2006) employ a model whereby the underlying resource distribution is controlled by a single parameter that acts as the exponent of a negative power law describing the sizes of randomly located patches. Animals move using a rule that divides resource value by distance for each patch, and then moves to the patch with the highest score. This model shows that a simple, environmentally determined foraging strategy without an inbuilt step length distribution responds as per a LW due to the distribution and size of resources available. As Santos and colleagues (2007) explain, the importance of this finding is that the walk pattern is entirely deterministic but resembles a stochastic process purely due to environmental noise. We arrive at a strategy which is fully reactive and varies with the environment, rather than one which has evolved due to prolonged existence in an environment of a particular type.

Linking Paths and Places in Archaeology

The above paragraphs give a very brief introduction to two of the debates currently in progress in the study of animal movement. Such debates, particularly as far as they impinge on the evolution of foraging strategies and their cognitive implications, are of clear relevance to archaeologists. It was noted in the introduction that archaeologists are faced with a very particular problem – that of effectively reanimating static material remains so as to arrive at inferences concerning past behavior. One of the principal doctrines of the New Archaeology, of which David Clarke was such a central figure, was that this should be achieved via application of the methods provided by the natural sciences. The analyses of "Lévy Walks in Hunter-Gatherers," and in particular their extension in "Archaeological Extensions and Implications," provide us with a means by which to adapt the methods of ecologists regarding animal movement to the distributions of lithics and other materials found in the archaeological record. As archaeologists, we are fortunate in that lithics provide an enduring record of the distributions of relict populations in space; in order to extract information about mobility, however, we must move beyond the distributions of lithics that form our basic data and examine the patterns of mobility most likely to have created them.

Conclusions

When Clarke (1968) first suggested the idea that random walk models could be employed in the simulation of archaeological processes, he probably envisioned neither the phenomenal growth of their use in biology and ecology nor their failure to penetrate "the empty mind behind the floral waistcoat" of establishment archaeology (Clarke, quoted in Hammond 1979:3). Quantitative approaches to archaeological data have moved on apace, however, with the many insights of *Analytical Archaeology* proving vital to this growing canon. The current paper has summarized some of the history of random walk models in biology and ecology, with a particular focus on recent studies of Lévy walks. The underlying theory and mathematics of these approaches are described, and an anthropological case study provides an example of their application. Discussion of the results of this application are followed by the presentation of a new method that allows for the extension of random walk analyses to archaeological datasets in which the walk segments are unknown; it is hoped that this method will provide a means by which archaeologists can compare and contrast the mobility strategies of foragers from different temporal periods and geographical areas.

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References

Adams, R.E.W. and Jones, R.C., 1997. Spatial patterns and regional growth among Classic Maya cities. *American Antiquity* 46: 301–322.

Alonso, D., Bartumeus, F. and Catalan, J., 2002. Mutual interference between predators can give rise to Turing spatial patterns. *Ecology* 83: 28–34.

Atkinson, R.P.D., Rhodes, C.J., Macdonald, D.W. and Anderson, R.M., 2002. Scale-free dynamics in the movement patterns of jackals. *Oikos* 98: 134–140.

Austin, D., Bowen, W.D. and McMillan, J.I., 2004. Intraspecific variation in movement patterns: modeling individual behavior in a large marine predator. *Oikos* 105: 15–30.

Bailey, H. and Thompson, P., 2006. Quantitative analysis of bottlenose dolphin movement patterns and their relationship with foraging. *Journal of Animal Ecology* 75: 456–465.

Bartumeus, F., 2007. Levy processes in animal movement: An evolutionary hypothesis. *Fractals – Complex Geometry Patterns and Scaling in Nature and Society* 15: 151–162.

Bartumeus, F., Catalan, J., Fulco, U.L., Lyra, M.L. and Viswanathan, G.M., 2002. Optimizing the encounter rate in biological interactions: Levy versus Brownian strategies. *Physical Review Letters* 88: 097901.

Bartumeus, F., Peters, F., Pueyo S., Marrase, C. and Catalan, J., 2003. Helical Lévy walks: adjusting searching statistics to resource availability in microzooplankton. *Proceedings of the National Academy of Sciences of the United States of America* 100: 12771–12775.

Benedix, J.H., 1993. Area-restricted search by the plains pocket gopher (Geomys-Bursarius) in tallgrass prairie habitat. *Behavioral Ecology* 4: 318–324.

Benhamou, S., 2007. How many animals really do the Lévy walk? *Ecology* 88: 1962–1969.

Benichou, O., Loverdo, C., Moreau, M. and Voituriez, R., 2007. A minimal model of intermittent search in dimension two. *Journal of Physics – Condensed Matter* 19: 065141.

Berg, H.C., 1983. *Random Walks in Biology*. Princeton University Press, Princeton.

Bergman, C.M., Schaefer, J.A. and Luttich, S.N., 2000. Caribou movement as a correlated random walk. *Oecologia* 123: 364–374.

Binford, L.R., 1978a. Dimensional analysis of behavior and site structure: learning from an Eskimo hunting stand. *American Antiquity* 43: 330–361.

Binford, L.R., 1978b. *Nunamiut Ethnoarchaeology*. Academic Press, London.

Binford, L.R., 1980. Willow smoke and dogs' tails: hunter-gatherer settlement systems and archaeological site formation. *American Antiquity* 45: 1–17.

Binford, L.R., 1982. The archaeology of place. *Journal of Anthropological Archaeology* 1: 5–31.

Binford, L.R., 2001. *Constructing Frames of Reference: An Analytical Method for Archaeological Theory Building Using Hunter-Gatherer and Environmental Data Sets*. University of California Press, Berkeley.

Blackwell, P.G., 1997. Random diffusion models for animal movement. *Ecological Modeling* 100: 87–102.

Bovet, P. and Benhamou, S., 1988. Spatial analysis of animals' movements using a correlated random walk model. *Journal of Theoretical Biology* 131: 419–433.

Boyer, D., Ramos-Fernandez, G., Miramontes, O., Mateos, J.L., Cocho, G., Larralde, H., Ramos, H. and Rojas, F., 2006. Scale-free foraging by primates emerges from their interaction with a complex environment. *Proceedings of the Royal Society B* 273: 1743–1750.

Boyle, K.V., 1996. From Laugerie Basse to Jolivet: the organization of Final Magdalenian settlement in the Vezere Valley. *World Archaeology* 27: 477–491.

Brantingham, P.J., 2003. A neutral model of stone raw material procurement. *American Antiquity* 68: 487–509.

Brantingham, P.J., 2006. Measuring forager mobility. *Current Anthropology* 47: 435–459.

Brown, C.T., 2001. The fractal dimensions of lithic reduction. *Journal of Archaeological Science* 28: 619–631.

Brown, C.T., Liebovitch, L.S. and Glendon, R., 2007. Levy flights in Dobe Ju/'hoansi foraging patterns. *Human Ecology* 35: 129–138.

Brown, C.T. and Witschey, W.R.T., 2003. The fractal geometry of ancient Maya settlement. *Journal of Archaeological Science* 30: 1619–1632.

Brown, C.T., Witschey, W.R.T. and Liebovitch, L.S., 2005. The broken past: Fractals in archaeology. *Journal of Archaeological Method and Theory* 12: 37–78.

Burger, O., Hamilton, M.J. and Walker, R., 2005. The prey as patch model: optimal handling of resources with diminishing returns. *Journal of Archaeological Science* 32: 1147–1158.

Chorley, R.J. and Haggett, P., 1967. *Models in Geography*. Methuen, London.

Clarke, D.L., 1968. *Analytical Archaeology*. Methuen, London.

Clarke, D.L., 1972. Models and paradigms in contemporary archaeology. In *Models in Archaeology*, edited by D.L. Clarke, pp. 1–80. Methuen, London.

Clarke, D.L., editor., 1977a. *Spatial Archaeology*. Academic Press, London.

Clarke, D.L., 1977b. Spatial information in archaeology. In *Spatial Archaeology*, edited by D.L. Clarke, pp. 1–32. Academic Press, London.

Clarke, D.L., 1979. *Analytical Archaeologist: Collected Papers of David L. Clarke*. Academic Press, London.

Cole, B.J., 1995. Fractal time in animal behavior – the movement activity of drosophila. *Animal Behaviour* 50: 1317–1324.

Coscoy, S., Huguet, E. and Amblard, F., 2007. Statistical analysis of sets of random walks: how to resolve their generating mechanism. *Bulletin of Mathematical Biology* 69: 2467–2492.

Crist, T.O., Guertin, D.S., Wiens, J.A. and Milne, B.T., 1992. Animal movement in heterogeneous landscapes – an experiment with Eleodes beetles in shortgrass prairie. *Functional Ecology* 6: 536–544.

da Luz, M.G.E., Buldyrev, S.V., Havlin, S., Raposo, E.P., Stanley, H.E. and Viswanathan, G.M., 2001. Improvements in the statistical approach to random Lévy flight searches. *Physica A – Statistical Mechanics and Its Applications* 295: 89–92.

Dai, X.H., Shannon, G., Slotow, R., Page, B. and Duffy, K.J., 2007. Short-duration daytime movements of a cow herd of African elephants. *Journal of Mammalogy* 88: 151–157.

de Knegt, H.J., Hengeveld, G.M., van Langevelde, F., de Boer, W.F. and Kirkman, K.P., 2007. Patch density determines movement patterns and foraging efficiency of large herbivores. *Behavioral Ecology* 18: 1065–1072.

Edwards, A.M., Phillips, R.A., Watkins, N.W., Freeman, M.P., Murphy, E.J., Afanasyev, V., Buldyrev, S.V., da Luz, M.G.E., Raposo, E.P., Stanley, H.E. and Viswanathan G.M., 2007. Revisiting Lévy flight search patterns of wandering albatrosses, bumblebees and deer. *Nature* 449: 1044–1048.

Einstein, A., 1905. Uber die von der molekularkinetischen theorie der warme geforderte bewegung von in ruhenden flussigkeiten suspendierten teilchen. *Annals of Physics* 17: 549–560.

Einstein, A., 1906. Zur theorie der Brownschen bewegung. *Annals of Physics* 19: 371–381.

Faugeras, B. and Maury, O., 2007. Modeling fish population movements: From an individual-based representation to an advection-diffusion equation. *Journal of Theoretical Biology* 247: 837–848.

Fritz, H., Said, S. and Weimerskirch, H., 2003. Scale-dependent hierarchical adjustments of movement patterns in a long-range foraging seabird. *Proceedings of the Royal Society of London Series B* 270: 1143–1148.

Gamble, C., 1983. Culture and society in the Upper Paleolithic of Europe. In *Hunter-Gatherer Economy in Prehistory*, edited by G.N. Bailey, pp. 201–211. Cambridge University Press, Cambridge.

Gamble, C., 1996. Making tracks: hominid networks and the evolution of the social landscape. In *The Archaeology of Human Ancestry: Power, Sex and Tradition*, edited by J. Steele and S.J. Shennan, pp. 253–277. Routledge, London.

Gamble, C., 1998. Paleolithic society and the release from proximity: a network approach to intimate relations. *World Archaeology* 29: 429–449.

Gamble, C., 1999. *The Paleolithic Societies of Europe*. Cambridge University Press, Cambridge.

Gautestad, A.O. and Mysterud, I., 1993. Physical and biological mechanisms in animal movement processes. *Journal of Applied Ecology* 30: 523–535.

Gautestad, A.O. and Mysterud, I., 1995. The home range ghost. *Oikos* 74: 195–204.

Gautestad, A.O. and Mysterud, I., 2005. Intrinsic scaling complexity in animal dispersion and abundance. *American Naturalist* 165: 44–55.

Gautestad, A.O. and Mysterud, I., 2006. Complex animal distribution and abundance from memory-dependent kinetics. *Ecological Complexity* 3: 44–55.

Gautestad, A.O., Mysterud, I. and Pelton, M.R., 1998. Complex movement and scale-free habitat use: testing the multiscaled home-range model on black bear telemetry data. *Ursus* 10: 219–234.

Gibson, E., 2007. The archaeology of movement in a Mediterranean landscape. *Journal of Mediterranean Archaeology* 20: 61–87.

Grove, M.J., 2008a. *The Evolution of Hominin Group Size and Land Use: An Archaeological Perspective*. Unpublished PhD Thesis, University of London, London.

Grove, M.J., 2008b. Estimating hunter-gatherer group size via spatio-allometric analysis. *PaleoAnthropology* 2008: e10.

Grove, M.J., 2009. Hunter-gatherer movement patterns: causes and constraints. *Journal of Anthropological Archaeology* 28: 222–233.

Grove, M.J., 2010. The archaeology of group size. *Proceedings of the British Academy* 158: 395–416.

Grove, M.J. and Coward, F., 2008. From individual neurons to social brains. *Cambridge Archaeological Journal* 18: 373–386.

Grunbaum, D., 1998. Schooling as a strategy for taxis in a noisy environment. *Evolutionary Ecology* 12: 503–522.

Hagerstrand, T., 1967. *Innovation Diffusion as a Spatial Process*. University of Chicago Press, Chicago.

Haggett, P., 1965. *Locational Analysis in Human Geography*. Edward Arnold Ltd., London.

Haggett, P., Cliff, A.D. and Frey, A., 1977. *Locational Analysis in Human Geography*. Arnold, London.

Hamilton, M.J., Milne, B.T., Walker, R.S., Burger, O. and Brown, J.H., 2007. The complex structure of hunter-gatherer social networks. *Proceedings of the Royal Society B* 274: 2195–2202.

Hammond, N., 1979. David Clarke: a biographical sketch. In *Analytical Archaeologist: Collected Papers of David L Clarke*, pp. 1–10. Academic Press, London.

Hancock, P.A. and Milner-Gulland, E.J., 2006. Optimal movement strategies for social foragers in unpredictable environments. *Ecology* 87: 2094–2102.

Harnos, A., Horváth, G., Lawrence, A.B. and Vattay G., 2000. Scaling and intermittency in animal behavior. *Physica A – Statistical Mechanics and its Applications* 286: 312–320.

Hays, G.C., Hobson, V.J., Metcalfe, J.D., Righton, D. and Sims, D.W., 2006. Flexible foraging movements of leatherback turtles across the North Atlantic Ocean. *Ecology* 87: 2647–2656.

Higgs, E.S. and Vita-Finzi, C., 1972. Prehistoric economies: a territorial approach. In *Papers in Economic Prehistory*, edited by E.S. Higgs, pp. 27–36. Cambridge University Press, Cambridge.

Hodder, I., 1979. Simulating the growth of hierarchies. In *Transformations: Mathematical Approaches to Culture Change*, edited by C. Renfrew and K.L. Cooke, pp. 117–144. Academic Press, New York.

Hodder, I. and Orton, C., 1976. *Spatial Analysis in Archaeology*. Cambridge University Press, Cambridge.

Houston, A.I. and McNamara, J.M., 1999. *Models of Adaptive Behaviour: An Approach Based on State*. Cambridge University Press, Cambridge.

Howell, N., 1976. The population of the Dobe Area !Kung. In *Kalahari Hunter-Gatherers: Studies of the !Kung San and Their Neighbours*, edited by R.B. Lee and I. DeVore, pp. 137–151. Harvard University Press, Cambridge, MA.

Howell, N., 1979. *Demography of the Dobe !Kung*. Academic Press, New York.

Isaac, G.L., 1981. Stone Age visiting cards: approaches to the study of early land use patterns. In *Pattern of the Past: Studies in Honour of David Clarke*, edited by I. Hodder, G.L. Isaac and N. Hammond, pp. 131–155. Cambridge University Press, Cambridge.

Johnson, A.R., Milne, B.T. and Wiens J.A., 1992. Diffusion in fractal landscapes – simulations and experimental studies of Tenebrionid beetle movements. *Ecology* 73: 1968–1983.

Johnson, D.S., London, J.M., Lea, M.A. and Durban, J.W., 2008. Continuous-time correlated random walk model for animal telemetry data. *Ecology* 89: 1208–1215.

Johnson, G.A., 1980. Rank-size convexity and system integration: a view from archaeology. *Economic Geography* 56: 234–247.

Johnson, G.A., 1980. Rank-size convexity and system integration: a view from archaeology. *Economic Geography* 56: 234–247.

Kareiva, P.M. and Shigesada, N., 1983. Analyzing insect movement as a correlated random walk. *Oecologia* 56: 234–238.

Kelly, R.L., 1983. Hunter-gatherer mobility strategies. *Journal of Anthropological Research* 39: 277–306.

Kelly, R.L., 1992. Mobility/sedentism – concepts, archaeological measures, and effects. *Annual Review of Anthropology* 21: 43–66.

Kelly, R.L., 1995. *The Foraging Spectrum: Diversity in Hunter-Gatherer Lifeways*. Smithsonian Institution Press, Washington.

Lee, R.B., 1976. !Kung spatial organization. In *Kalahari Hunter-Gatherers: Studies of the !Kung San and Their Neighbours*, edited by R.B. Lee and I. DeVore, pp. 73–97. Harvard University Press Cambridge, MA.

Levandowsky, M., Klafter, J. and White B.S., 1988a. Feeding and swimming behavior in grazing microzooplankton. *Journal of Protozoology* 35: 243–246.

Levandowsky, M., Klafter, J. and White B.S., 1988b. Swimming behavior and chemosensory responses in the protistan microzooplankton as a function of the hydrodynamic regime. *Bulletin of Marine Science* 43: 758–763.

Levandowsky, M., White, B.S. and Schuster, F.L., 1997. Random movements of soil amebas. *Acta Protozoologica* 36: 237–248.

Lévy, P., 1937. *Theorie de l'Addition des Variables Aleatoires*. Gauthier-Villars, Paris.

Liebovitch, L.S., Scheurle, D., Rusek, M. and Zochowski, M., 2001. Fractal methods to analyze ion channel kinetics. *Methods* 24: 359–375.

Liebovitch, L.S., Todorov, A.T., Zochowski, M., Scheurle, D., Colgin, L., Wood, M.A., Ellenbogen, K.A., Herre, J.M. and Bernstein, R.C., 1999. Nonlinear properties of cardiac rhythm abnormalities. *Physical Review E* 59: 3312–3319.

Mandelbrot, B.B., 1983. *The Fractal Geometry of Nature*. W.H. Freeman and Company, New York

Marell, A., Ball, J.P. and Hofgaard. A., 2002. Foraging and movement paths of female reindeer: insights from fractal analysis, correlated random walks, and Lévy flights. *Canadian Journal of Zoology – Revue Canadienne De Zoologie* 80: 854–865.

McAndrews, T.L., Albarracin-Jordan, J. and Bermann, M., 1997. Regional settlement patterns in the Tiwanaku Valley of Bolivia. *Journal of Field Archaeology* 24: 67–83.

Morales, J.M., Haydon, D.T., Frair, J., Holsiner, K.E. and Fryxell, J.M., 2004. Extracting more out of relocation data: Building movement models as mixtures of random walks. *Ecology* 85: 2436–2445.

Newman, M.E.J., 2005. Power laws, Pareto distributions and Zipf's law. *Contemporary Physics* 46: 323–351.

Ogata, Y. and Katsura, K., 1991. Maximum likelihood estimates of the fractal dimension for random spatial patterns. *Biometrika* 78: 463–474.

Okubo, A., 1980. *Diffusion and Ecological Problems: Mathematical Models*. Springer-Verlag, Berlin.

Patlak, C.S., 1953a. Random walk with persistence and external bias. *Bulletin of Mathematical Biophysics* 15: 311–338.

Patlak, C.S., 1953b. A mathematical contribution to the study of orientation of organisms. *Bulletin of Mathematical Biophysics* 15: 431–476.

Pearson, C.E., 1980. Rank-size distributions and the analysis of prehistoric settlement systems. *Journal of Anthropological Research* 36: 453–462.

Pearson, K., 1905. The problem of the random walk. *Nature* 72: 294.

Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., 2007. *Numerical Recipes: The Art of Scientific Computing*. Cambridge University Press, Cambridge.

Ramos-Fernandez, G. and Ayala-Orozco, B., 2003. Population size and habitat use in spider monkeys at Punta Laguna, Mexico. In *Primates in Fragments: Ecology and Conservation*, edited by L.K. Marsh, pp. 191–210. Kluwer Academic Publishers, New York.

Ramos-Fernandez, G., Boyer D. and Gomez, V.P., 2006. A complex social structure with fission–fusion properties can emerge from a simple foraging model. *Behavioral Ecology and Sociobiology* 60: 536–549.

Ramos-Fernandez, G., Mateos, J.L., Miramontes, O., Cocho, G., Larralde, H. and Ayala-Orozco, B., 2004. Levy walk patterns in the foraging movements of spider monkeys (*Ateles geoffroyi*). *Behavioral Ecology and Sociobiology* 55: 223–230.

Raposo, E.P., Buldyrev, S.V., da Luz, M.G.E., Santos, M.C., Stanley, H.E. and Viswanathan, G.M., 2003. Dynamical robustness of Lévy search strategies. *Physical Review Letters* 91: 240601.

Rayleigh, L., 1905. The problem of the random walk. *Nature* 72: 318.

Reid, A.T., 1953. On stochastic processes in biology. *Biometrics* 9: 275–289.

Reynolds, A.M., 2007. Avoidance of conspecific odour trails results in scale-free movement patterns and the execution of an optimal searching strategy. *Europhys Lett* 79: 30006

Reynolds, A.M., 2008. Optimal random Levy-loop searching: new insights into the searching behaviors of central-place foragers. *Europhys Lett* 82: 20001

Reynolds, A.M. and Frye, M.A., 2007. Free-flight odor tracking in *Drosophila* is consistent with an optimal intermittent scale-free search. *PloS One* 2: e354.

Reynolds, A.M., Reynolds, D.R., Smith, A.D., Svensson, G.P. and Lofstedt, C., 2007a. Appetitive flight patterns of male *Agrotis segetum* moths over landscape scales. *Journal of Theoretical Biology* 245: 141–149.

Reynolds, A.M., Smith, A.D., Menzel, R., Greggers, U., Reynolds, D.R. and Riley. J.R., 2007b. Displaced honey bees perform optimal scale-free search flights. *Ecology* 88: 1955–1961.

Reynolds, A.M., Smith, A.D., Reynolds, D.R., Carreck, N.L. and Osborne, J.L., 2007c. Honeybees perform optimal scale-free searching flights when attempting to locate a food source. *Journal of Experimental Biology* 210: 3763–3770.

Ricotta, C., 2000. From theoretical ecology to statistical physics and back: self-similar landscape metrics as a synthesis of ecological diversity and geometrical complexity. *Ecological Modeling* 125: 245–253.

Rodseth, L., Wrangham, R.W., Harrigan, A.M. and Smuts B.B., 1991. The human community as a primate society. *Current Anthropology* 32: 221–254.

Rudnick, J. and Gaspari, G., 2004. *Elements of the Random Walk*. Cambridge University Press, Cambridge.

Santos, M.C., Boyer, D., Miramontes, O., Viswanathan, G.M., Raposo, E.P., Mateos, J.L. and da Luz, M.G.E., 2007. Origin of power-law distributions in deterministic walks: the influence of landscape geometry. *Physical Review E* 75: 061114.

Schaefer, J.A., Bergman, C.M. and Luttich S.N., 2000. Site fidelity of female caribou at multiple spatial scales. *Landscape Ecology* 15: 731–739.

Shlesinger, M.F. and Klafter, J., 1986. Levy walks versus Levy flights. In *On Growth and Form*, edited by H.E. Stanley and N. Ostrowski, pp. 279–283. Martinus Nijhof Publishers, Amsterdam.

Sims, D.W., Righton, D. and Pitchford, J.W., 2007. Minimizing errors in identifying Levy flight behavior of organisms. *Journal of Animal Ecology* 76: 222–229.

Sims, D.W., Southall, E.J., Humphries, N.E., Hays, G.C., Bradshaw, C.J.A., Pitchford, J.W., James, A., Ahmed, M.Z., Brierley, A.S., Hindell, M.A., Morritt, D., Musyl, M.K., Righton, D., Shepard, E.L.C., Wearmouth, V.J., Wilson, R.P., Witt, M.J. and Metcalfe, J.D., 2008. Scaling laws of marine predator search behavior. *Nature* 451: 1098–1102.

Sims, D.W., Witt, M.J., Richardson, A.J., Southall, E.J. and Metcalfe, J.D., 2006. Encounter success of free-ranging marine predator movements across a dynamic prey landscape. *Proceedings of the Royal Society B – Biological Sciences* 273: 1195–1201.

Skellam, J.G., 1951. Random dispersal in theoretical populations. *Biometrika* 38: 196–218.

Skellam, J.G., 1973. The formulation and interpretation of mathematical models of diffusionary processes in population biology. In *The Mathematical Theory of the Dynamics of Biological Populations*, edited by M.S. Bartlett and R.W. Hiorns, pp. 63–85. Academic Press, London.

Stephens, D.W. and Krebs J.R., 1986. *Foraging Theory*. Princeton University Press, Princeton.

Travis, J., 2008. How a shark finds its next meal. *ScienceNOW Daily News*, http://sciencenow.sciencemag.org/cgi/content/full/2008/227/1.

Turchin, P., 1998. *Quantitative Analysis of Movement: Measuring and Modeling Population Redistribution in Animals and Plants*. Sinauer Associates, Sunderland, MA.

Viswanathan, G.M., Afanasyev, V., Buldyrev, S.V., Havlin, S., da Luz, M.G.E., Raposo, E.P. and Stanley, H.E., 2000. Levy flights in random searches. *Physica A* 282: 1–12.

Viswanathan, G.M., Afanasyev, V., Buldyrev, S.V., Havlin, S., da Luz, M.G.E., Raposo, E.P. and Stanley, H.E., 2001. Levy fights search patterns of biological organisms. *Physica A* 295: 85–88.

Viswanathan, G.M., Afanasyev, V., Buldyrev, S.V., Murphy, E.J., Prince, P.A. and Stanley, H.E., 1996. Levy flight search patterns of wandering albatrosses. *Nature* 381: 413–415.

Viswanathan, G M., Bartumeus, F., Buldyrev, S.V., Catalan, J., Fulco, U.L., Havlin, S., da Luz, M.G.E., Lyra, M.L., Raposo, E.P. and Stanley, H.E., 2002. Levy flight random searches in biological phenomena. *Physica A – Statistical Mechanics and Its Applications* 314: 208–213.

Viswanathan, G.M., Buldyrev, S.V., Havlin, S., da Luz, M.G.E., Raposo, E.P. and Stanley, H.E., 1999. Optimizing the success of random searches. *Nature* 401: 911–914.

Viswanathan, G.M., Raposo, E.P. and da Luz, M.G.E., 2008. Lévy flights and superdiffusion in the context of biological encounters and random searches. *Physics of Life Reviews* 5: 133–150.

Vita-Finzi, C. and Higgs, E.S., 1970. Prehistoric economy in the Mount Carmel area of Palestine: site catchment analysis. *Proceedings of the Prehistoric Society* 36: 1–37.

Ward, D. and Saltz D., 1994. Foraging at different spatial scales – Dorcas gazelles foraging for lilies in the Negev Desert. *Ecology* 75: 48–58.

Whallon, R., 2006. Social networks and information: non-"utilitarian" mobility among hunter-gatherers. *Journal of Anthropological Archaeology* 25: 259–270.

Yellen, J.E., 1976. Settlement patterns of the !Kung. In *Kalahari Hunter-Gatherers: Studies of the !Kung San and Their Neighbours*, edited by R.B. Lee and I. DeVore, pp. 47–72. Harvard University Press, Cambridge, MA.

Yellen, J.E., 1977. *Archaeological Approaches to the Present: Models for Reconstructing the Past*. Academic Press, New York.

Zhang, X.X., Johnson, S.N., Crawford, J.W., Gregory, P.J. and Young, I.M., 2007. A general random walk model for the leptokurtic distribution of organism movement: theory and application. *Ecological Modeling* 200: 79–88.

Zhou, W.X., Sornette, D., Hill, R.A. and Dunbar, R.I.M., 2005. Discrete hierarchical organization of social group sizes. *Proceedings of the Royal Society B* 272: 439–444.

Zipf, G.K., 1949. *Human Behaviour and the Principle of Least Effort*. Addison-Wesley, Cambridge.

Zubrow, E.B.W., 1985. Fractals, cultural behavior, and prehistory. *American Archeology* 5: 63–77.

Chapter 6
Metrical Variability Between South Asian Handaxe Assemblages: Preliminary Observations

Parth R. Chauhan

Abstract The Indian subcontinent represents the easternmost abundant source of classic Acheulean technology in the Old World. Since the late nineteenth century, a large number of Acheulean sites have been reported from India, Pakistan, and most recently Nepal. This study focuses exclusively on handaxes and attempts to respectively compare published metrical data from individual assemblages and groups of assemblages with each other, using univariate and multivariate statistical methods (cluster analyses and the *Mann–Whitney U* test). The five main variables that are examined include mean values of handaxe length, breadth, thickness, and elongation and "refinement," to reveal levels of statistical metric differences between handaxe groups and associated typological and geographic patterns. Preliminary results indicate that many of these handaxe assemblages are not metrically distinguishable as strictly Early or Late Acheulean types, as has been done in the past. While the handaxe assemblages geographically closest to each other broadly cluster together at the locality level (albeit inconsistently), there are significant statistical differences between groups of assemblages at *interregional* levels. This indicates that there was marked geographic and probably chronological overlap in the *degrees* of metric variation across the entire Indian subcontinent, possibly reflecting a dynamic intermediate developmental phase within the region following initial colonization by Acheulean hominins.

Introduction

Research on Acheulean handaxes has pervaded Paleolithic archaeology for nearly two centuries and continues to draw significant attention up to today. Studies of handaxes have included qualitative descriptions, quantification of typotechnological attributes, geochronological applications, experimental flintknapping, actualistic butchery and new analytical methods to understand the Acheulean from novel perspectives (e.g., Soressi and Dibble 2003; Machin et al. 2007; Goren-Inbar and

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Sharon 2006; Lycett and von Cramon-Taubadel 2008). Though several regional comparisons or studies of Acheulean bifaces exist for evidence from Europe, Africa, the Levant, and East Asia (e.g., Crompton and Gowlett 1993; Hou et al. 2000; Saragusti and Goren-Inbar 2001; Norton et al. 2006; Santonja and Villa 2006; de la Torre et al. 2008), comparable studies utilizing biface data from the Indian subcontinent remain comparatively rare (e.g. Wynn and Tierson 1990; McPherron 2000; Noll and Petraglia 2003). Several factors are responsible for this: (1) very few Acheulean sites in the subcontinent have been properly excavated and dated (e.g., Pappu et al. 2003); (2) the data is not easily accessible to Western researchers; or (3) specific required information (e.g., technological descriptions, metrical details) is often lacking or is available in varying detail. While multiple metrical studies have been conducted for individual assemblages (e.g., Joshi and Marathe 1975–1976; Pappu and Akilesh 2006) or groups of sites (e.g., Semans 1981; Gaillard et al. 1990), a broader comparative study of all available South Asian hand axe metrical data has never been carried out.

This paper represents a preliminary attempt to examine the available metrical data (namely for length, breadth, thickness, elongation, and "refinement") at both inter-assemblage and interregional levels through univariate and multivariate statistics. The main motivation for this study was the large number of Acheulean sites now known in the subcontinent and their diverse typological and dimensional range. In addition, while metric studies have been carried out for individual sites or to compare two to four assemblages with each other, the published metric data has never been utilized before to compare *all* South Asian assemblages as a whole. This study represents an attempt to answer three basic questions regarding the metrical attributes of the South-Asian handaxe data: (1) When metric variables are ranked, do assemblages group according to traditional typo-chronological (i.e., "Early" vs. "Late") expectations?; (2) Which South Asian handaxe assemblages are metrically most similar to each other?; (3) Are some groups of South Asian assemblages statistically different from each other and is there a geographic pattern to this?

The South Asian Acheulean Record

The South Asian Lower Paleolithic record has been traditionally divided into core-and-flake and bifacial lithic industries (Jayaswal 1982; Chauhan 2010); the latter being the better known and longer studied technology (Pappu 2001a; Petraglia 2006; Chauhan 2009). Most of the South Asian assemblages include typical tool types found at other Acheulean sites in the Old World (Petraglia 2006) but show differences in their respective proportions of choppers, handaxes, and cleavers, probably related to regionally varied ecology, functions, and raw materials (Jayaswal 1978; Ghosh 1985). The current distribution of Acheulean sites in the region illustrates successful colonizations of a wide range of ecological zones across the subcontinent. With the exception of northeast India and parts of Konkan Maharashtra, western Kerala, south of the Kaveri River, and Sri Lanka, Acheulean assemblages are found throughout

most of the subcontinent. They occur in montane regions, hill slopes, alluvial/fluvial settings, coastal plains, stabilized sand dunes, springs, lakes and pools, marine or littoral zones, and with bedrock outcrops (Misra 1989). In contrast to East and Southeast Asia, hundreds of Acheulean sites and scatters have been reported (Petraglia 2006). Most are open-air sites, while a few occurrences have been reported from caves or rock shelters. Sites are particularly rich in the central and southern Eastern Ghats and less frequent on the northern Deccan plateau, the latter attributed to the lack of stratigraphic preservation or the weathering of basalt artifacts (Mishra 1982).

Most of the Indian Paleolithic localities have been directly dated through the Uranium-Thorium (^{234}Th-^{230}U) and thermoluminescense (TL) methods and include a predominance of Acheulean sites (Mishra 1995; Petraglia 1998). Ages for other occurrences in the subcontinent such as Dina, Jalalpur, Morgaon, and Satpati Hill have been estimated using paleomagnetism and geostratigraphic correlations. Although biochronology has been utilized at some sites (e.g., Hathnora), it is not a reliable indicator of age because Pleistocene faunal assemblages in peninsular India often occur in secondary coarse-grained contexts and the First and Last Appearance Datums of many taxa are yet to be accurately pinpointed (Chauhan 2008). Most of the dated sites appear to be situated in the Middle and Late Pleistocene, although some localities such as Morgaon, for example, may extend into the terminal Early Pleistocene. The first early radiometric age determination for an Acheulean assemblage was obtained from the Bori tephra in the Kukdi Valley in the Deccan Plateau (ca. 1.38 Ma), but the date was later rejected because the ash was correlated to the Younger Toba Tuff event of ca. 74 Ka (Mishra et al. 1995; Petraglia 1998). Later, two of three Ar/Ar samples yielded ages of 680 and 660 Ka respectively (Deo et al. 2007), highlighting the need for more accurate dates from other sites. At Didwana, Teggihalli, Chirki-Nevasa, and Yedurwadi, the ^{234}Th-^{230}U ages for the Acheulean extend beyond 350 (or 390 Ka in the case of Didwana for the Lower Paleolithic, bifaces being absent), the maximum limit of the dating methods, an assessment partly supported by lithic typology. Slightly younger Middle Pleistocene ages were obtained from vertebrate fossils teeth in stratigraphic association with Acheulean tools that were dated to between 287 and 290 Ka at Teggihalli (from the same layer as the date of >350 ka) and Sadab, also in the Hunsgi Valley.

With the possible exceptions of the Satpati Hill site in Nepal and Morgaon and Chirki-on-Pravara in Maharashtra, there is no unequivocal evidence of Acheulean occupation prior to the Middle Pleistocene in the subcontinent. The site of Isampur in the Hunsgi Valley has been recently dated to ca. 1.27 Ma using electron spin resonance (ESR) on herbivore teeth associated with the cultural horizons (Paddayya et al. 2002). However, this estimate is preliminary and requires corroboration, given the possibility of geological reworking (B. Blackwell: pers. comm.) and current problems with ESR on Indian faunal specimens in specific depositional conditions (e.g., Blackwell et al. 2007). The youngest dates for the Acheulean come from Umrethi (>190 Ka) and Adi Chadi Wao (ca. 69 Ka) in Gujarat, Bhimbetka (ca. >106 Ka) in Madhya Pradesh and Kaldevanhalli in Karnataka (166 and 174 Ka) (Marathe 1981; Szabo et al. 1990; Bednarik et al. 2005). The terminal Acheulean evidence is not well established, and the use of diminutive bifaces persisted well into the Upper Pleistocene presumably as parts

of early Middle Paleolithic assemblages (Misra 1989). Detailed information about individual sites, site clusters and associated contextual, chronological, and behavioral interpretations can be found in the numerous reviews (Sankalia 1974; Paddayya 1984; Misra 1987, 1989; Mishra 2006–2007; Petraglia 2006; Pappu 2001a; Korisettar 2002; Chauhan 2009).

The South Asian Acheulean has often been divided into Early or Late developmental phases, based primarily on typo-technological features, assemblage compositions, comparative stratigraphy, and associated metrical analyses (Paddayya 1984; Misra 1987; Pappu 2001a; Petraglia 2006). Early Acheulean assemblages are known to comprise handaxes, choppers, polyhedrons, and spheroids, usually a lower number of cleavers (but not always) and flake tools, the predominant use of the stone-hammer technique, and a marked absence of the Levallois technique (Misra 1987). The Early Acheulean bifaces are often thought to be asymmetrical, large with thick butts or midsections and possess large, bold and irregular flake scars, indicative of hard-hammer percussion. In contrast, Late Acheulean assemblages have been defined by the low proportion of bifaces, the high ratio of cleavers to hand axes, the very high ratio of flake tools such as scrapers, and the extensive employment of the soft-hammer technique and the Levallois and discoid-core techniques (Misra 1987). The bifaces are also generally smaller, thinner, and more refined, with a significant increase in the degree of retouching and controlled bifacial thinning/flaking.

However, South Asian Acheulean handaxes comprise a diverse typological and metric range and include lanceolates, ovates, micoquians, cordiforms, "pear-shaped," and "almond shaped," among others. There is also a large variation between these types in terms of their size and shape, probably a result of raw material type, form and quality, personal preferences, regional styles, functional aspects, and so forth. Although key technomorphological differences suggest that the "Early vs. Late Acheulean" division is probably chronologically applicable (albeit broadly and conditionally), previous researchers have rarely taken into account other causal factors such as age, manufacturing stages, raw material constraints and artifact functions (Petraglia 1998). Therefore, due to the absence of absolute dates, one of the main aims of this study was to statistically distinguish between Early and Late Acheulean assemblages using available metric mean values for select variables.

Goals and Methodology

Following the pioneering Acheulean biface studies by Bordes (1961) and Roe (1964, 1968) in the 1960s, some researchers soon began applying the same statistical methods to the Indian Acheulean data at varying capacities. In almost all these studies, the methods of biface orientation and measurements used were standardized and generally consistent, and applied to both surface and stratified biface assemblages. While some publications offer summary statistical data on both handaxes and cleavers (e.g., Kumar 1989), data for handaxe assemblages is comparatively greater than for cleaver assemblages. One major problem encountered at the outset was the discrepancy in the amount of published metrical data available, a critical

factor that restricted the degree and types of metrical comparisons possible in this study. For example, majority of the publications provide mean data only for the five primary variables - length, breadth, thickness, "elongation," and "refinement"[1] – and thus these became the focus of this study. Unfortunately, values for additional pertinent attributes such as shape/typology, flake scars counts, weight, and related metrical values such as B1, T1, and so forth, are currently available from a very limited number of sites and thus could not be included in this analysis. Likewise, many of these publications do not always provide such relevant statistical information as standard deviation and coefficient of variation, even though means are mentioned. Some publication(s) provided mean length values but not breadth and thickness values, for example, and as a result, such assemblages were suitable only for the univariate comparisons. In short, very few statistical studies on the South Asian Acheulean data are comprehensive or near-comprehensive in nature; some appreciable exceptions are those by Misra (1967), Gaillard et al. (1986, 1990), Raju (1988), Sinha (1991), and Pappu and Akilesh (2006).

Almost all handaxe assemblages utilized in this study come from India and a few assemblages come from Pakistan and Nepal (Fig. 6.1). For Nepal, measurements of only a single specimen are currently available (Corvinus 2006) but were included in the inter-assemblage study to avoid exclusion of a key geographic region of the subcontinent. With the exception of an unpublished assemblage from Pilikarar in the central Narmada Basin (Chauhan 2004; Sharma and Sharma 2005; Patnaik et al. 2009; Chauhan and Patnaik 2008) and one doctoral dissertation (Supekar 1968), all utilized handaxe data come from published literature (e.g. Bose and Sen 1948; Krishnaswami and Soundarajan 1951; Joshi 1955; Khatri 1958; Bose et al. 1960; Misra and Nagar 1961–1962; Misra 1962; Misra 1963; Mohapatra 1962; Khatri 1958, 1963, 1964; Misra 1967; Pappu 1970–1971; Pappu 1974; Jacobson 1975; Joshi and Marathe 1975–1976; Sankalia 1976; Misra 1977; Paddayya 1977; Allchin et al. 1978; Rao 1979; Marathe 1981; Mohapatra 1981; Semans 1981; Mohapatra 1981, 1982; Blumenschine et al. 1983; Chakrabarti 1983; Kenoyer and Pal 1983; Misra et al. 1983; Rao 1983; Reddy and Bhaskar 1983; Bopardikar 1985; Raju 1985; Gaillard et al. 1986; Chakrabarti and Lahiri 1987; Chakrabarti and Chattopadhyay 1988; Gaillard and Murty 1988; Raju 1988; Kumar 1989; Rishi 1989; Lal and Salahuddin 1989–1990; Ashraf 1990; Bhaskar 1990; Gaillard et al. 1990; Singh and Singh 1990; Sinha 1991; Chakrabarti 1993; Ansari and Pappu 1973; Sharma 1993; Behera et al. 1996; Biagi et al. 1996; Misra 1997; Mohanty et al. 1997; Pappu 2001b; Deotare et al. 2004; Sharma et al. 2004; Corvinus 2006; Pappu and Akilesh 2006). Unfortunately, most of this information is not widely accessible, especially to Western researchers. Through this study, an important source for reference, in the form of metrical data from a large number of South Asian handaxe assemblages, is now available for the first time here for future large-scale

[1] It is now well known that the "refinement" index is a poor or unreliable indicator for assessing the actual techno-morphological refinement (in the true sense) of any given Acheulean biface assemblage (e.g., Norton et al. 2006). The values compiled and sorted in this study and associated statistical observations further attest to this fact, and therefore, "refinement" is meant to be understood as *relative*-thickness throughout the paper.

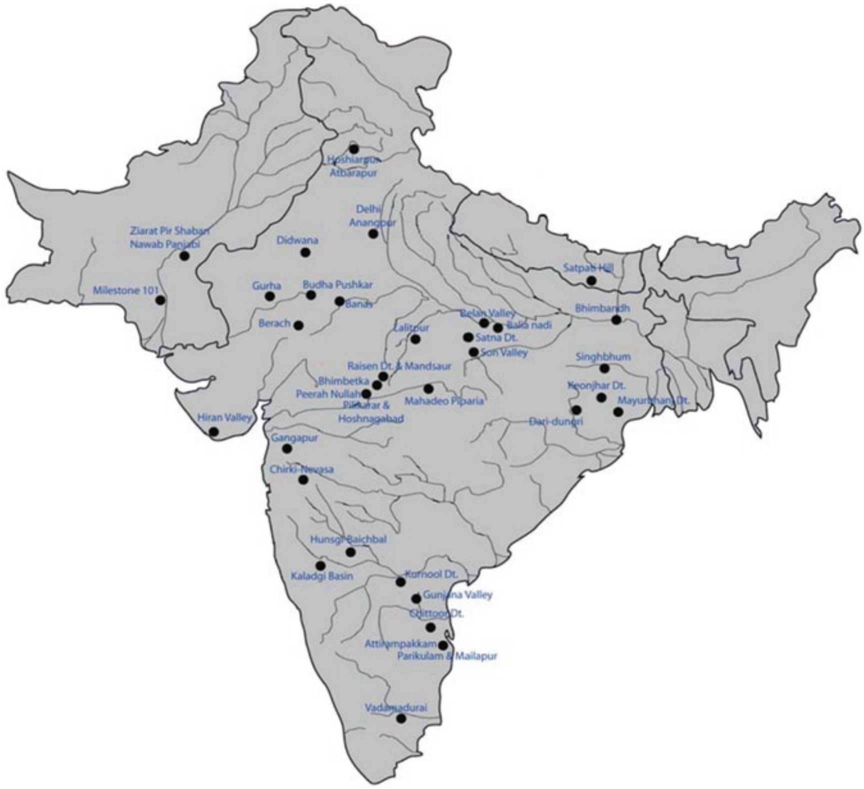

Fig. 6.1 Locational map of some of the most important South Asian handaxe assemblages utilized in this study

global comparisons. For detailed descriptions and other information on the individual sites and assemblages utilized in this study, readers are encouraged to refer to the relevant citations.

The first methodological step for the current study involved compiling the mean values for length, breadth, thickness, elongation (breadth/length), and refinement (thickness/breadth) from the available literature. To be as comprehensive and unbiased as possible, sites for which mean values were not available were included in the analyses by calculating their means from published measurements of individual specimens.[2] Therefore, with the exception of some single specimens from Nepal for example, the majority of assemblages utilized consist of 2–250 handaxe specimens. For the inter-assemblage analysis, a total of 247 handaxe assemblages were utilized and for the interregional study, many of these assemblages were arbitrarily combined into regional groups – all representing metric values from a total of 2,564 handaxe specimens (Table 6.1). For the inter-assemblage study, each assemblage represents a

[2] To be as comprehensive as possible, mean metric values were calculated for 50 additional assemblages from measurements of over 300 individual specimens available in the literature.

Table 6.1 Main list of handaxes assemblages used in this study and their associated metric values and sources of reference

Site or area	Occurrences	Specimens	L	L-SD	B	B-SD	T	T-SD	B/L	T/B	T/L	Reference
Pakistan												
Milestone 101	5	47	13.03	–	7.3	–	3.47	–	–	–	–	Allchin et al. (1978)
Ovates (Milestone 101)	1	2	10.3		7.2	–	3.2	–	–	–	–	Ibid.
Rohri Hills												
Nawab Punjabi, Site 3*	1	1	10.6	–	5.3	–	3.5	–	0.5	0.66	0.33	Allchin et al. (1978)
Ziarat Pir Shaban*	1	14	15.94	1.22	9.18	0.9	4.65	0.57	0.58	0.51	0.29	Biagi et al. (1996)
Nepal												
Satpati Hill*	1	1	17.5	–	10.5	–	4.7	–	0.6	0.45	0.27	Corvinus (2006)
Punjab												
Hoshiarpur area	Mult.	9	14.2	–	9.3	–	4.6	–	–	–	–	Mohapatra (1981, 1982)
Hoshiarpur area (4 sp. for indices only)*	1		15.43	6.63	8.95	4.05	4.95	1.27	0.58	0.6	0.34	Ibid.
Atbarapur*	1	9	15.49	4.38	9.84	1.57	4.76	1.66	0.66	0.49	0.31	Rishi (1989)
Delhi-Haryana												
Bhaunkri-II*	1	2	14.2	5.37	10.55	4.88	4.5	0.99	0.73	0.45	0.33	Chakrabarti and Lahiri (1987)
JNU Hills*	1	2	13.95	0.07	8.3	0.99	3.7	0.42	0.59	0.45	0.27	Ibid.
Meola Pahari I*	1	2	10.9	1.41	6.55	1.2	2.75	0.07	0.6	0.43	0.25	Ibid.
SOS Children's Village*	1	1	13	–	7	–	2.9	–	0.54	0.41	0.22	Ibid.
Above 4 combined		7	13.01	2.72	8.26	2.71	3.54	0.89	0.63	0.44	0.27	
Anangpur*	1	15	15.95	2.98	10.37	1.34	4.73	1.52	0.66	0.46	0.3	Sharma (1993)
Bihar												
Bhimbandh (Monghyr Dt.)*	1	5	15.94	1.22	9.18	0.9	4.65	0.57	0.58	0.51	0.29	Bose et al. (1960)

(continued)

Table 6.1 (continued)

Site or area	Occurrences	Specimens	L	L-SD	B	B-SD	T	T-SD	B/L	T/B	T/L	Reference
Manipur												
Singtom*	1	1	11.7	–	8.2	–	3.3	–	0.7	0.4	0.28	Singh and Singh (1990)
Arunachal Pradesh												
Pachin*	1	1	13.8	–	7.4	–	3.9	–	0.54	0.53	0.28	Ashraf (1990)
Poma*	1	1	15.5	–	9.4	–	5.4	–	0.61	0.57	0.35	Ibid.
Uttar Pradesh												
Belan Valley												
Chhatarpalia	1	29	14.42	–	9.54	–	4.98	–	–	–	–	Misra (1997)
Ramgarhwa	1	2	13.8	–	7.7	–	4.4	–	–	–	–	Ibid.
Koskan garha	1	5	15.28	–	10.94	–	5.74	–	–	–	–	Ibid.
Deogarh	1	25	11.7	–	8.2	–	3.9	–	–	–	–	Lal and Salahuddin (1989–1990)
Balia Nadi (Singrauli Basin)*	1	2	15.7	13.2	8	5.94	6.15	5.16	0.54	0.73	0.39	Krishnaswami and Soundarajan (1951)
Lalitpur (Bundelkhand region)*	1	3	16.7	4.89	8.73	2.11	4.13	0.42	0.53	0.49	0.26	Sankalia (1976)
Rajasthan												
Western Rajasthan												
Luni*	1	2	9.85	2.33	6.75	0.35	3.05	0.64	0.7	0.45	0.31	Misra (1963)
Srinagari*	1	1	11.2	–	5.8	–	2.8	–	0.52	0.48	0.25	Ibid.
Dhaneri*	1	1	10.7	–	5.6	–	2.8	–	0.52	0.5	0.26	Ibid.
Lordiya*	1	1	11	–	7.5	–	3	–	0.68	0.4	0.27	Deotare et al. (2004)
Above 4 combined		5	10.52	1.33	6.48	0.8	2.94	0.34	0.62	0.46	0.28	
Berach Basin (southern Rajasthan)												
Berach Industry	6	22	11.63	2.15	8.05	1.74	3.91	1.09	0.68	0.49	0.34	Misra (1967)
Gambhiri Industry (Chittorgarh)	1	25	13.38	2.91	8.05	1.74	4.58	1.31	0.68	0.49	0.35	Ibid.

Gambhiri Industry (Chittorgarh)*		20		13.09	2.34	7.64	2.12	4.75	2.41	0.58	0.63	0.36	Khatri (1958)
Above 2 combined			45	13.24	2.63	7.845	1.93	4.665	1.86	0.63	0.56	0.36	
Wagan Industry	4	35		10.6	1.95	7.1	1.42	3.8	0.98	0.67	0.54	0.36	Misra (1967)
Kadmali Industry	1	8		12.2	–	7.7	–	4.4	–	0.63	0.56	–	Ibid.
Kalyanpura (Kadmali)*	1	2		12.9	0.57	8.1	0.42	4.6	0.42	0.63	0.57	0.36	Khatri (1958)
Wagan MSA	3	7		8.9	–	5.6	–	3.5	–	0.68	0.63	–	Misra (1967)
Didwana area (northern Rajasthan)													
Singi Talav (SGT)	1	120		12.78	2.6	7.8	1.38	4.38	1.12	0.62	0.57	–	Gaillard et al. (1986, 1990) for B/L
Indola-ki-dhani (IDL)	1	8		9.83	2.5	6.94	1.44	4.05	1.09	–	0.58	–	Gaillard et al. (1986)
Amarpura (APR)	1	4		11.7	3	8.63	1.67	4.45	1.11	–	0.51	–	Ibid.
Koliya Hills (KLY-H)	1	64		11.81	2.3	8.23	1.23	3.86	0.97	–	0.49	–	Ibid.
Koliya (surface of Amarpura Fm.) (KLY-A)	1	10		9.91	2.1	6.97	0.91	3.54	0.49	–	0.53	–	Ibid.
Bandlav-ki-talav A (BLT-A)	1	10		9.61	1.3	6.62	1.09	3.81	0.62	–	0.48	–	Ibid.
Bandlav-ki-talav D (BLT-D)	1	11		7.55	0.8	5.68	0.56	2.91	0.85	–	0.51	–	Ibid.
Surabi-Talav (SBT)	1	5		9.86	1.5	6.94	0.7	3.26	0.56	–	0.47	–	Ibid.
KLY-A (pooled)	1	36		9.14	1.8	6.63	1.11	3.11	0.74	–	0.5	–	Ibid.
Jankipura (JPR)	1	17		11.5	3	7.38	1.03	3.74	1	–	0.52	–	Ibid.
Jayal (JYL-S and JYL-T)	1	52		10.89	2.2	7.44	1.23	3.92	0.8	–	0.53	–	Ibid.

(continued)

Table 6.1 (continued)

Site or area	Occurrences	Specimens	L	L-SD	B	B-SD	T	T-SD	B/L	T/B	T/L	Reference
Central Rajasthan												
Gurha	1	3	12.12	–	7.93	–	4.9	–	–	–	–	Allchin et al. (1978)
Savitri Hill	1	3	12.55	–	8.25	–	4.9	–	–	–	–	Ibid.
Hokra 2B*	1	1	18.6	–	9.4	–	6.5	–	0.51	0.69	0.35	Ibid.
Marwar Bagra*	1	1	16.4	–	10.2	–	6	–	0.62	0.59	0.37	Ibid.
Mogara*	1	1	11.5	–	8.6	–	2.8	–	0.75	0.33	0.24	Ibid.
Kota*	1	2	13.1	0.28	8.9	0	3.45	0.78	0.68	0.39	0.26	Misra and Nagar (1961–1962)
Above 4 combined		5	14.54	2.89	9.2	0.63	4.44	1.73	0.65	0.48	0.3	
Banas Valley (eastern Rajasthan)												
Banthali*	1	2	14.8	3.68	10.55	4.31	6.4	4.81	0.7	0.56	0.4	Misra (1962)
Sarupganj*	1	2	12.3	0.99	8.2	0.42	4.1	0.71	0.67	0.5	0.33	Ibid.
Tonk*	1	2	12.95	7	8.15	3.04	4.2	2.12	0.66	0.5	0.33	Ibid.
Bigod*	1	1	12.3	–	6.7	–	3.9	–	0.54	0.58	0.32	Ibid.
Deoli*	1	1	11.5	–	7.1	–	3.2	–	0.62	0.45	0.28	Ibid.
Jahahpur*	1	1	9.1	–	5.9	–	2.6	–	0.65	0.44	0.29	Ibid.
Mandpia*	1	1	12.2	–	8.8	–	5.8	–	0.72	0.66	0.48	Ibid.
Above 7 combined		10	12.52	3.11	8.23	2.31	4.49	2.19	0.66	0.53	0.35	
Gujarat												
Hiran Valley*	1	9	14.93	2.46	9.04	2.45	5.56	1.51	0.61	0.62	0.37	Marathe (1981)
Bhajodi (Kutch)*	1	2	11.55	2.05	8.1	2.69	4.9	0.14	0.69	0.64	0.43	Ansari and Pappu (1973)
Pedhamli (Sabarmati Valley)*	1	1	10	–	8.6	–	3.4	–	0.86	0.4	0.34	Sankalia (1976)
Rajpipla (Karjan Valley)*	1	1	13.9	–	9.2	–	6.7	–	0.66	0.73	0.48	Ibid.
Saurashtra region												
Rojadi*	1	3	11	1	6.07	0.98	3.1	0.53	0.55	0.51	0.28	Sankalia (1976); Chakrabarti (1983)
Samadhiala*	1	1	11	–	6.6	–	3.2	–	0.6	0.48	0.29	Chakrabarti (1983)

Dharangadhra*	1	2		11.25	1.48	7.6	0.14	3.5	0.14	0.68	0.46	0.31	Chakrabarti (1983)
Above 3 combined			6	11.08	0.93	6.67	0.98	3.25	0.39	0.6	0.49	0.29	
Madhya Pradesh													
Maihar	1	55		12.52	–	8.35	–	4.43	–	–	–	–	Misra (1977)
Mandsaur (eastern Malwa)*	1	11		13.98	2.84	7.86	1.77	4.26	1.42	0.57	0.56	0.31	Khatri (1963)
Raisen Dt. (eastern Malwa)	18	45		11.38	–	7.7	–	4.32	–	–	–	–	Jacobson (1975)
Son Valley (Bilaspur Dt.)													
Nawatola*	1	1		13	–	6.8	–	3.5	–	0.52	0.51	0.27	Ahmad (1978–79)
Salamtota*	1	1		13.9	–	7.9	–	5.1	–	0.57	0.65	0.37	Ibid.
Above 2 combined			2	13.45	0.64	7.35	0.78	4.3	1.13	0.55	0.58	0.32	
Son Valley													
Hatwa	1	44		13.13	–	8.9	–	4.23	–	–	–	–	Misra (1997)
Sihawal	1	49		12.5	–	9.1	–	5.34	–	–	–	–	Ibid.
Patpara-a	1	41		11.47	–	7.94	–	3.61	–	–	–	–	Ibid.
Sihawal II*	1	1		16	–	10.2	–	6.9	–	0.64	0.68	0.43	Kenoyer and Pal (1983)
Patpara-b*	1	10		11.02	3.75	7.33	1.83	3.24	1.06	0.68	0.44	0.3	Blumenschine et al. (1983)
Nakjhar Khurd (surface)	1	11		14.29	2.46	7.77	0.976	3.75	0.78	0.56	0.48	0.26	Misra et al. (1983)
Nakjhar Khurd (Patpara Fm.)	1	9		13.13	2.48	7.48	1.493	4	0.99	0.57	0.54	0.31	Ibid.
Satna Dt.													
Sharda Temple-I	1	6		12.8	1.65	9.7	1.37	5	1.47	0.76	0.51	0.38	Sinha (1991)
Sharda Temple-II	1	14		11.2	1.93	8.3	1.53	4.1	0.66	0.73	0.5	0.36	Ibid.
Sharda Temple-III	1	12		11.6	1.84	8.4	0.85	4.8	1.16	0.73	0.57	0.42	Ibid.
Sharda Temple-IV	1	4		13.7	1.77	10.5	1.37	5.8	1.76	0.77	0.57	0.43	Ibid.
Naru Hill	1	6		12.7	2.95	9.9	2.73	5.3	0.88	0.77	0.56	0.44	Ibid.
Tikura	1	2		11.4	0.56	9.7	0.98	5.4	1.62	0.84	0.57	0.48	Ibid.
Bhimbetka (BTK)	1	67		12.84	3	–	–	4.28	1.2	–	0.5	–	Gaillard et al. (1986)

(continued)

Table 6.1 (continued)

Site or area	Occurrences	Specimens	L	L-SD	B	B-SD	T	T-SD	B/L	T/B	T/L	Reference
Near Hoshangabad (Narmada)												
Pilikarar	1	20	13.78	2.96	8.8	1.686	4.82	0.93	0.645	0.55	0.35	Chauhan and Patnaik (2008)
Hoshangabad (Budni gravels)*	1	5	14.06	3.11	7.88	1.08	4.82	0.82	0.57	0.63	0.36	Khatri (1964)
Hoshangabad (Bhagwara gravels)*	1	2	14.3	0.28	7.75	1.63	5.8	0.14	0.54	0.76	0.41	Ibid.
Opp. Hoshangabad (Bhagwara II gravels)*	1	1	15.3	–	8.5	–	5.1	–	0.56	0.6	0.33	Ibid.
Hoshnagabad*	1	3	10.47	1.61	7.87	1.36	5.6	1.65	0.76	0.7	0.55	Supekar (1968)
Above 4 combined		11	13.24	2.77	7.91	1.07	5.24	1	0.62	0.67	0.42	
Hasalpur gravels*	1	1	13.3	–	10.6	–	7.5	–	0.8	0.71	0.56	Khatri (1962)
Dongarwara*	1	1	16.3	–	9.1	–	6.6	–	0.56	0.73	0.4	
Hasalpur*	1	2	15.8	0.42	9.95	0.49	4.5	0.57	0.63	0.45	0.29	Supekar (1968)
Above 3 combined		4	15.3	1.38	9.9	0.68	5.78	1.55	0.65	0.59	0.38	
Near Narsimhpur (Narmada)												
Devakachhar upper sands of R. Sher*	1	1	14.7	–	8.6	–	4.2	–	0.59	0.49	0.29	Khatri (1964)
Barurewa River, Devakachhar*	1	1	15.9	–	8.4	–	5.6	–	0.53	0.67	0.35	Ibid.
Above 2 combined		2	15.3	0.85	8.5	0.14	4.9	0.99	0.56	0.58	0.32	
Mahadeo Piparia*	1	1	23.8	–	12.3	–	9.6	–	0.52	0.78	0.4	Khatri (1962)
Mahadeo Piparia*		7	14.39	3.38	9.57	1.24	5.56	0.93	0.68	0.59	0.4	Supekar (1968)
Peerah, Garra and Keolari streams	3	38	13.7	2.48	9.11		4.7	–	0.68	0.52	–	Semans (1981)
Peerah Nullah*	1	3	15.73	3.13	8.33	1.07	6.6	0.98	0.54	0.79	0.43	Supekar (1968)

Jharkhand													
Palamau Dt.													
Maila Bridge*	1	1		8.5	–	5.2	–	2.8	–	0.61	0.54	0.33	Chakrabarti and Chattopadhyay (1988)
Jorkot*	1	1		9	–	8	–	3.6	–	0.89	0.45	0.4	Ibid.
Above 2 combined			2	8.75	0.35	6.6	1.98	3.2	0.57	0.75	0.49	0.36	
Hazaribagh Dt.													
Paradih*	1	2		11.85	3.32	7.7	2.55	3.75	1.06	0.65	0.49	0.32	Chakrabarti (1993)
Pundra*	1	1		13.5	–	9.4	–	4.4	–	0.7	0.47	0.33	Ibid.
Above 2 combined			3	12.4	2.54	8.27	2.05	3.97	0.84	0.66	0.48	0.32	
Singhbhum Dt.													
Uldah*	1	1		17.3	–	8.1	–	2.8	–	0.47	0.35	0.16	Chakrabarti (1993)
Bichhati-Dungri*	1	1		18	–	8.5	–	3.7	–	0.47	0.44	0.21	Ibid.
Maheshpur*	1	1		15.2	–	8.2	–	3.9	–	0.54	0.48	0.26	Ibid.
Patbera*	1	1		14	–	8.3	–	3.4	–	0.59	0.41	0.24	Ibid.
Hat Gamharia*	1	1		14.2	–	7	–	3	–	0.49	0.43	0.21	Ibid.
Tatibe or Tebo*	1	2		13.25	1.77	7.55	0.78	2.5	0.42	0.58	0.34	0.19	Ibid.
Purnapani*	1	1		15.3	–	9.8	–	7	–	0.64	0.71	0.46	Ibid.
Barudih*	1	1		14.3	–	7.7	–	3	–	0.54	0.39	0.21	Ibid.
Lapso-Kyanite*	1	2		12.8	1.13	9.95	0.64	4.85	0.49	0.78	0.49	0.38	Ibid.
Jojodih*	1	2		16.35	5.87	9.15	2.9	4.55	2.33	0.56	0.48	0.27	Ibid.
Swaspur*	1	2		16.85	1.63	9.1	1.56	3.3	0.14	0.54	0.37	0.2	Ibid.
Bamni*	1	1		14.5	–	8.7	–	3.2	–	0.6	0.37	0.22	Ibid.
Chakuria*	1	1		21.1	–	12.8	–	3	–	0.61	0.23	0.14	Ibid.
Terga*	1	1		17		6.5		4.8		0.38	0.74	0.28	Ibid.
Above 14 combined			18	15.52	2.67	8.73	1.64	3.79	1.28	0.57	0.49	0.28	
Santal Parganas Dt.													
Saola*	1	1		12.5	–	7.1	–	3.5	–	0.57	0.49	0.28	Chakrabarti (1993)
Maharashtra													
Gangapur	1	17		11.79	1.7	7.41	1.1	3.32	0.7	0.64	0.42	0.27	Kumar (1989)

(continued)

Table 6.1 (continued)

Site or area	Occurrences	Specimens	L	L-SD	B	B-SD	T	T-SD	B/L	T/B	T/L	Reference
Chirki-on-Pravara	1	88	13.79	3.77	7.6	0.3	4.88	1.26		0.64		Joshi and Marathe (1975–1976)
Nevasa*	1	3	15.93	5.56	8.2	2.33	4.77	0.74	0.52	0.62	0.33	Sankalia (1976)
Manegaon (Jalgaon Dt.)*	1	2	11.85	1.91	8.55	0.07	4	1.98	0.73	0.47	0.33	Bopardikar (1985)
Kathora*	1	1	15.2	–	9.6	–	6.6	–	0.63	0.69	0.43	Sankalia (1976)
Orissa												
Dari-dungri (below 5 types combined)	1	75	12.22	2.7	7.647	1.349	4.006	0.85	0.678	0.53	0.35	Behera et al. (1996)
Cordiform		19	9.5	2.5	7.021	1.58	3.584	1.03	0.75	0.51	0.38	
Amygdaloid		17	13.42	2.75	7.794	1.292	4.324	0.69	0.59	0.56	0.33	
Limande		15	13.42	2.75	7.28	1.887	4.14	1.03	0.57	0.58	0.33	
Ovate		14	12.89	2.75	8.7	1.301	4	0.85	0.74	0.46	0.34	
Sub-triangular		10	11.9	2.75	7.44	0.686	3.98	0.65	0.74	0.53	0.39	
Mayurbhanj Dt.												
Gengaraj, Joshipur, Kalabadia	3	15	16.07		8.36		4.26					Mohanty et al. (1997)
Kalabaria*	1	6	13.45	2.48	8.47	1.75	4.42	1.52	0.64	0.52	0.32	Bose and Sen (1948)
Bankathi*	1	6	12.22	2.47	7.72	1.22	4.52	1.13	0.64	0.59	0.37	Chakrabarti and Chattopadhyay (1988)
Kadopani*	1	1	17.4	–	10.8	–	6.3	–	0.62	0.58	0.36	Ibid.
Banskathia*	1	1	13	–	7.2	–	5.2	–	0.55	0.72	0.4	Ibid.
Damodarpur*	1	1	13.2	–	9.2	–	3	–	0.7	0.33	0.23	Ibid.
Above 3 combined		3	14.53	2.48	9.07	1.8	4.83	1.68	0.62	0.54	0.33	
Keonjhar Dt.												
Kuliana*	1	16	13.28	2.97	8.06	1.62	4.6	1.14	0.62	0.58	0.35	Bose and Sen (1948)
Kolmunda*	1	1	8.5	–	6.6	–	2.8	–	0.78	0.42	0.33	Chakrabarti and Chattopadhyay (1988)
Nuaberi*	1	1	17.7	–	11.8	–	7.3	–	0.67	0.62	0.41	Bose and Sen (1948)

Bhuasuni*	1	1		19.4	–	11.8	–	5.9	–	0.61	0.5	0.3	Ibid.
Above 3 combined			3	15.2	5.86	10.07	3	5.33	2.3	0.68	0.51	0.35	
Harichandanpur*	1	11		11.38	2.46	7.48	1.38	3.82	0.82	0.67	0.51	0.34	Mohapatra (1962)
Pallahara*	1	16		12.93	1.85	8.35	1.35	3.86	0.53	0.65	0.47	0.3	Ibid.
Kaliakata*	1	5		15.12	5.08	9.28	2.09	4.58	1.03	0.65	0.49	0.32	Ibid.
Parang*	1	4		9.63	1.47	6.85	0.62	4.43	1.01	0.72	0.65	0.48	Ibid.
Barasol*	1	2		14.7	2.83	8.85	0.49	5.75	1.06	0.61	0.65	0.39	Ibid.
Bhalitundi*	1	1		14.1	–	9.4	–	3.7	–	0.67	0.39	0.26	Ibid.
Bijatala*	1	1		11.2	–	7.8	–	2.9	–	0.7	0.37	0.26	Ibid.
Bisai*	1	1		11.3	–	5.6	–	3.6	–	0.5	0.64	0.32	Ibid.
Champua*	1	1		13.8	–	8.8	–	3.7	–	0.64	0.42	0.27	Ibid.
Ghantasila*	1	1		11.7	–	10.4	–	4.5	–	0.89	0.43	0.38	Ibid.
Jangra*	1	1		12.7	–	8.2	–	4.2	–	0.65	0.51	0.33	Ibid.
Kankili*	1	1		10.1	–	8	–	3.4	–	0.79	0.43	0.34	Ibid.
Kharagprasad*	1	1		13.3	–	8.7	–	4.2	–	0.65	0.48	0.32	Ibid.
Kulei*	1	2		11.7	3.96	8.35	1.91	5.4	1.27	0.73	0.65	0.47	Ibid.
Mahulia*	1	1		12.1	–	7.6	–	4	–	0.63	0.53	0.33	Ibid.
Meramandali*	1	1		12	–	9.2	–	4.4	–	0.77	0.48	0.37	Ibid.
Muchurigaria*	1	1		12.8	–	6.6	–	4	–	0.52	0.61	0.31	Ibid.
Pratappur*	1	3		17.07	1.69	9.6	0.53	5.27	0.35	0.56	0.55	0.31	Ibid.
Satkuta*	1	1		11.8	–	9	–	4.5	–	0.76	0.5	0.38	Ibid.
Talcher*	1	1		8.4	–	6	–	2.9	–	0.71	0.48	0.35	Ibid.
Above 16 combined			20	12.97	2.62	8.43	1.33	4.41	0.98	0.66	0.53	0.34	
Andhra Pradesh													
Rallakalava Valley (Renigunta)													
Kummarivaripalli	1	9		8.92	0.67	6.42	0.85	3.44	0.96	–	0.53	–	Gaillard and Murty (1988)
Guravarajupalli	1	24		12.5	2.98	8.01	1.73	4.26	1.08	–	0.54	–	Ibid.
Guravarajupalli	1	34		12.45	4.7	8.35	3.1	4.41	2.1	0.68	0.54	–	Gaillard et al. (1990)

(continued)

Table 6.1 (continued)

Site or area	Occurrences	Specimens	L	L-SD	B	B-SD	T	T-SD	B/L	T/B	T/L	Reference
Above 2 combined		58	12.48	3.84	8.18	2.415	4.335	1.59	0.68	0.54	–	
Vedullacheruvu	1	46	11.14	4.5	7.22	2.2	3.52	1.7	0.67	0.48	–	Gaillard et al. (1990)
Paleru Valley, Prakasam Dt.	18	172	9.8	1.74	6.89	1.06	3.06	0.66	–	0.44	–	Rao (1979, 1983)
Gunjana Valley												
Netivaripalli (NVP)	1	78	10.92	2	7.321	1.28	3.23	0.8	0.69	0.44		Raju (1988)
Venkatarajupalli (URP/VRP)	1	66	11.15	1.84	7.65	1.26	3.24	0.85	0.68	0.44		Ibid.
Tummachetlapalli (TCP)	1	55	13.66	2.87	8.56	1.65	4.39	1.76	0.64	0.49		Ibid.
Narayana Nellore (NNR)	1	38	13.08	2.59	8.55	1.37	3	1.47	0.67	0.48		Ibid.
Chittoor Dt.												
Yarlapudi Kalva Basin (handaxes)	13	250	10.5	–	7.4	–	3.9	–	–	–	–	Bhaskar (1990)
Yarlapudi Kalva Basin (miniature handaxes)		92	7.2	–	5.7	–	2.9	–	–	–	–	Ibid.
Kurnool Dt.												
Chintapalli*	1	1	10.8	–	3.3	–	3.6	–	0.31	1.09	0.33	Sharma et al. (2004)
Kachchira*	1	2	14.6	3.39	9.1	1.56	6.85	2.33	0.65	0.79	0.46	Ibid.
Reta*	1	1	9	–	6.9	–	3.2	–	0.77	0.46	0.36	Ibid.
Above 3 combined		4	12.25	3.43	7.1	2.88	5.13	2.41	0.59	0.78	0.4	
Chintalapalem	1	38	9.2	–	6.2	–	3	–	0.669	0.6	–	Reddy and Bhaskar (1983)
Maratipelam	1	32	10	–	6.7	–	3.2	–	0.659	0.49	–	Ibid.
Karnataka												
Hunsgi Locality V trench 3	1	18	13.4	–	–	–	–	–	0.61	0.53	–	Paddayya (1977)
Malaprabha Basin												
Khyad*	1	17	16.8	5.1	9.32	1.66	5.42	1.35	0.58	0.59	0.34	Joshi (1955); Sankalia (1976)
Menasgi*	1	8	14.24	2.27	8.68	1.44	5.44	1.9	0.62	0.63	0.38	Joshi (1955)

Taminhal*	1	2		15.75	7.42	10.05	4.17	5.85	0.21	0.65	0.64	0.42	Ibid.
Maneri*	1	1		12.9	–	8.1	–	5	–	0.63	0.62	0.39	Ibid.
Hire-Mulangi*	1	1		17	–	7.4	–	4.2	–	0.44	0.57	0.25	Ibid.
Alur* and Alur Talakwad*	1	2		13.05	3.46	7.1	0	4.6	2.12	0.56	0.65	0.39	Ibid.
Chik-Mulangi*	1	1		10.2	–	6.5	–	5	–	0.64	0.77	0.49	Ibid.
Kallapur*	1	1		13.2	–	8.4	–	3	–	0.64	0.36	0.23	Ibid.
Yedhalli (Bijapur Dt.)*	1	1		10.5	–	6	–	3.5	–	0.57	0.58	0.33	Pappu (1970–1971)
Above 8 combined			9	13.49	3.71	7.86	2.06	4.62	1.22	0.59	0.61	0.37	
Anagwadi*	1	16		13.38	2.12	7.54	1.05	4.51	0.64	0.57	0.6	0.34	Pappu (1974)
Tamil Nadu													
Kortallyar Basin													
Attirampakkam	1	32		13.09	–	8.195	–	4.502	–	0.64	0.58	–	Pappu and Akilesh (2006)
Nambakkam	1	3		11.7	–	8.7	–	3	–	–	–	–	Pappu (2001b)
Mailapur	1	3		10.2	–	7.5	–	2.7	–	–	–	–	Ibid.
Parikulam*	1	10		14.1	–	9.5	–	4.2	–	–	–	–	Ibid.
Multiple locations in basin		19		25	–	10	–	3.5	–	–	–	–	Ibid.
Erumaivettipalayam*	1	1		8.79	–	3.45	–	4.95	–	0.39	1.43	0.56	Ibid.
Senrayanpalayam*	1	1		14	–	10	–	3	–	0.71	0.3	0.21	Ibid.
Above 2 combined			2	11.4	3.68	6.725	4.632	3.975	1.38	0.55	0.87	0.39	
Multiple sites throughout state*		11		9.54	2.75	6.35	1.49	3.18	0.64	0.69	0.51	0.35	Sharma et al. (2004)
Vadamadurai*	1	8		11.19	3.87	7.35	1.78	3.83	1.31	0.69	0.53	0.35	Ibid.
Total occurrences and handaxes	247	2,564											

*Signifies metric data calculated from published individual specimen measurements.

single site or a single collection from one general location. For the interregional study, two or more sites (usually in very close proximity) were occasionally combined (when required) to obtain mean values for that area or general location. As an example of the latter, one set of mean length, breadth, thickness, elongation, and refinement values was calculated using available measurements of seven handaxe specimens from four sites in the Delhi area to "generate" a single assemblage for the Delhi area to represent that specific region. If means were not calculated in this manner for some areas (i.e., using individual specimens from two or more sites close to each other), the overall sample size would have been considerably diminished and key geographic zones would have been underrepresented or not at all. This was not required nor done for the inter-assemblage cluster analysis because the objective in that study was to examine *only individual sites or discrete locations against each other*, rather than groups of assemblages (i.e., multiple sites/locations in one general locality or basin) against each other.

Following the compilation of the mean values, histograms were generated to confirm the normal distribution of the unilinear mean values and their usefulness for such a comparative study (Fig. 6.2). This simple exercise demonstrates that, instead of being techno-morphologically dissimilar to Acheulean types (e.g. Norton et al. 2006), the South Asian handaxe assemblages broadly fall within standard Acheulean metrical ranges as known from Africa, Europe and the Levant.[3] For example, regression computed between the three variables show a strong relationship or statistical correlation between them, the highest between length and breadth, followed by breadth and thickness and then length and thickness (Fig. 6.3). Regression between these three variables and associated elongation and refinement values, computed for both the grouped assemblages and individual specimens, further emphasize the *classic* technological nature of the South Asian Mode 2 industries. For example, four scatter plots and associated R^2 values illustrate that length is the most dominant variable affecting elongation (0.267 and 0.242, respectively), while thickness is the most dominant variable affecting refinement (0.465 and 0.455, respectively) (Fig. 6.4). Finally, there is also an inverse relationship, though not as acute as the previous ones, between elongation and refinement at the group-means level ($R^2=0.056$) but more pronounced at the individual-specimen level ($R^2=0.142$). In short, values for the least amount of elongation correlate best with values for the greatest refinement (Fig. 6.5). Although such regression results are commonly known from most Acheulean assemblages in general (e.g., Gowlett 1996), they have never been formally illustrated for the South Asian evidence in such a near-comprehensive manner.

Overall, the five metric variables, alone or variably combined, are not adequate for evincing the technochronological characters of individual assemblages (i.e., Early vs.

[3] These broad metrical similarities between the South Asian evidence and other Acheulean datasets do not preclude the existence of atypical biface assemblages within the Indian Subcontinent. In other words, several Mode 2 manufacturing traditions/cultures may have existed within the South Asian Lower Paleolithic, all of which have been traditionally recognized as belonging to the single "classic Acheulean tradition" (see Lycett and Gowlett 2008).

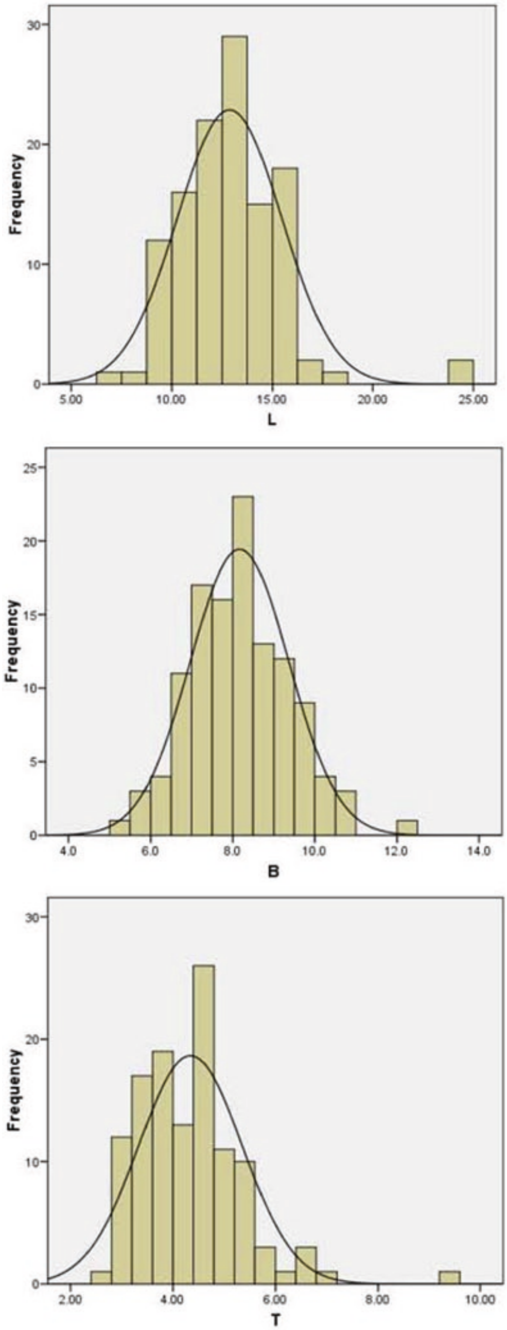

Fig. 6.2 Histograms generated for all studied handaxes using length, breadth and thickness values (*top to bottom*), respectively

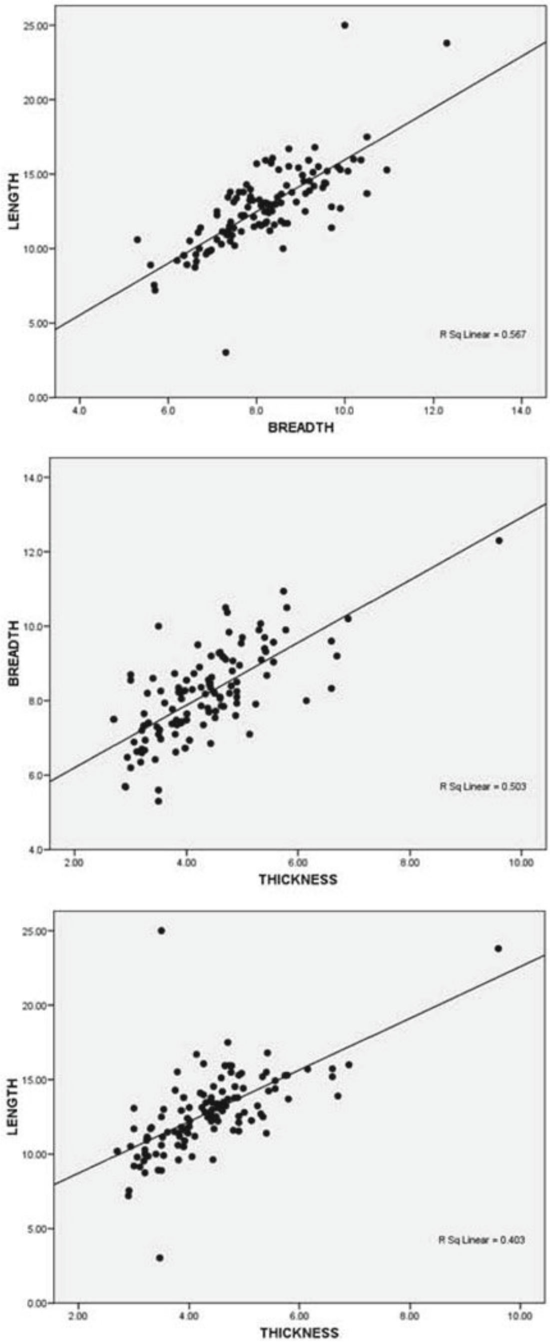

Fig. 6.3 Regression figures generated for all three linear variables against each other

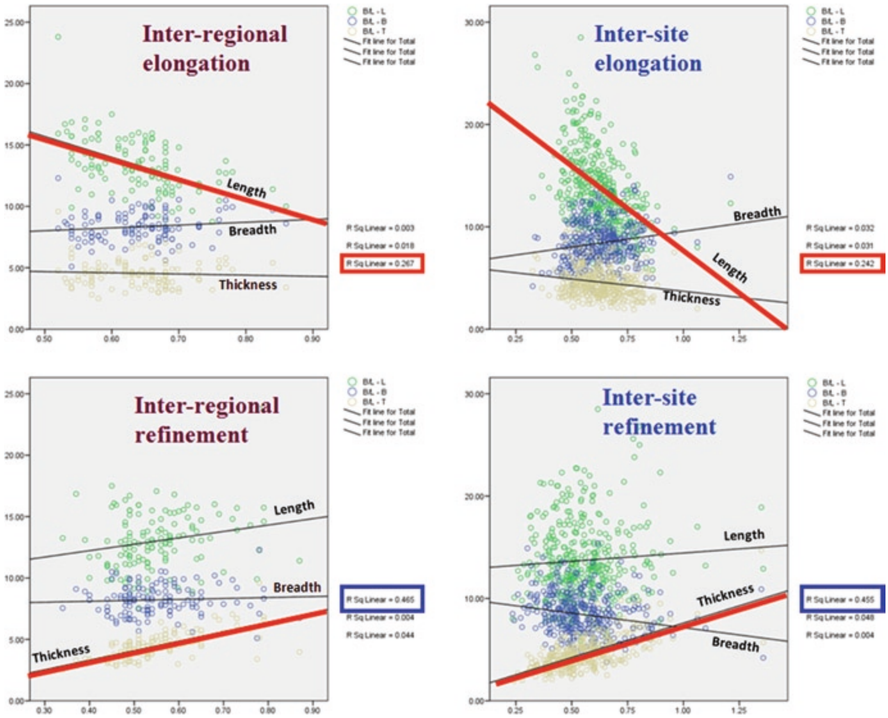

Fig. 6.4 Regression figures generated for inter-assemblage and inter-group elongation and refinement values

Late Acheulean). Due to this high level of metrical variability between the South Asian handaxe assemblages than previously known, the overarching goal of this study was to compare them with each other at inter-assemblage and interregional levels. Three main questions addressed in this study are:

Question 1: When metric variables are ranked, do assemblages group according to traditional typochronological (i.e., “Early” vs. “Late”) expectations?
Question 2: Which South Asian handaxe assemblages are metrically most similar to each other?
Question 3: Are some groups of South Asian assemblages statistically different from each other and is there a geographic pattern to this?

All statistical tests were undertaken using SPSS Version 15.0. For the inter-assemblage comparison (Question 2), three dendrograms were generated using a hierarchical cluster analysis to see which sites grouped together based respectively on their metrical data. The first dendrogram took into account the three main unilinear measurements – length, breadth, and thickness – available from 108 assemblages; the second dendrogram involved clustering based solely on elongation and refinement values available from 76 assemblages, and the third dendrogram incorporated all five variables available from 75 assemblages. For the interregional comparison

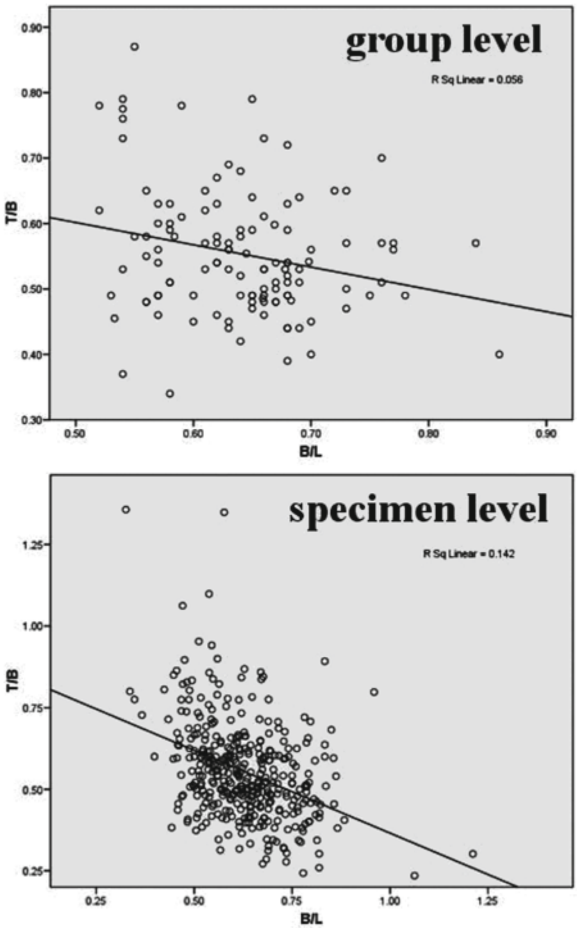

Fig. 6.5 Regression figures generated for elongation and refinement against each other at both inter-assemblage and inter-group levels

(Question 3), individual handaxe assemblages were arbitrarily separated into 29 regional groups based on their spatial or geographic proximity to each other. Following this division, the Mann–Whitney *U*-test was applied for multiple pairwise comparisons of all groups against each other involving all five variables respectively. The Mann–Whitney *U*-test is a nonparametric equivalent of the independent samples *t*-test, but unlike the latter it does not make assumptions about the homogeneity of variances or normal distributions within the sampled population (Dytham 2003). The groups of handaxe assemblages utilized in this study are all made up of 2–11 assemblages each. For example, the Didwana group represents 11 assemblages in close proximity to each other while the 2 assemblages in northeast India and Nepal and the 8 assemblages in Tamil Nadu are more widely dispersed in those respective regions. This is precisely why the Mann–Whitney *U*-test was deemed most suitable for this type of study.

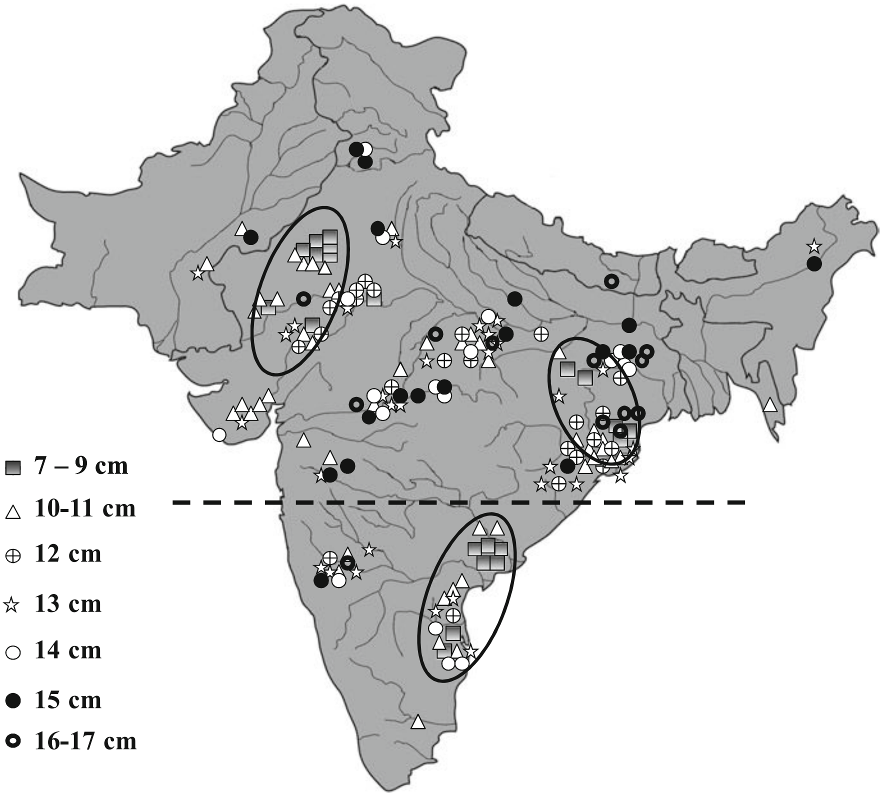

Fig. 6.6 Locational map showing the distribution of the handaxe assemblages across the Indian subcontinent based only on mean length values. Note the geographic distribution and clustering of the smallest (*yellow*) and largest (*black* and *orange*) handaxes

When the individual assemblages were mapped according to their lengths or length brackets for example, a very general regional pattern is visible (Fig. 6.6). The most outstanding feature is that assemblages with the smallest handaxes (in yellow) are located in three main locations. It is obvious that in some locations, where clasts were dimensionally restricted, the bifaces produced would be proportionate. In this case however, the distributional pattern of the smallest handaxe assemblages does not appear to be linked with raw material size constraints. The largest specimens (represented by black and orange, respectively) are predominantly found above the red dashed line, which may be a result of several possible reasons: (1) large geographic areas still require proper surveys – especially zones with low surface visibility such as thick forested areas such as tracts of Kerala – which may still yield comparably large handaxes; till now, for example, most Paleolithic surveys have focused on river valleys and some basins; (2) in some regions, there may be a preservation bias (e.g., size sorting, surface weathering) or collection bias by previous researchers who did not make systematic or comprehensive collections; (3) intensive resharpening/reduction strategies may have reduced larger handaxes into smaller specimens over time

(McPherron 1994) at some locations; (4) some zones where larger handaxes are absent may be a result of constraints in raw material size; (5) if the larger handaxes predominantly belong to the South Asian Early Acheulean facies, than the current pattern of size distribution may indicate that it only marginally penetrated southern (and northeastern) India while the Late Acheulean (i.e., smaller handaxes) is found everywhere; this possible explanation requires absolute dates. That being said, the sheer number of handaxe specimens included in this study from various regions of the subcontinent, most probably rules out any negative impacts of such survey, collection, or preservation biases on the statistical results.

When the assemblages were mapped according to their refinement values (Fig. 6.7), the most refined assemblages (in yellow) do overlap with the smallest assemblages, which is not surprising. These most refined and smallest assemblages may possibly belong to the early Middle Paleolithic. While intermediate refinement levels (in green) are found throughout India, the least refined assemblages (in purple) appear to dominate the western region with two exceptions in the east. Interestingly, there does not appear to be a clear geographic overlap between the

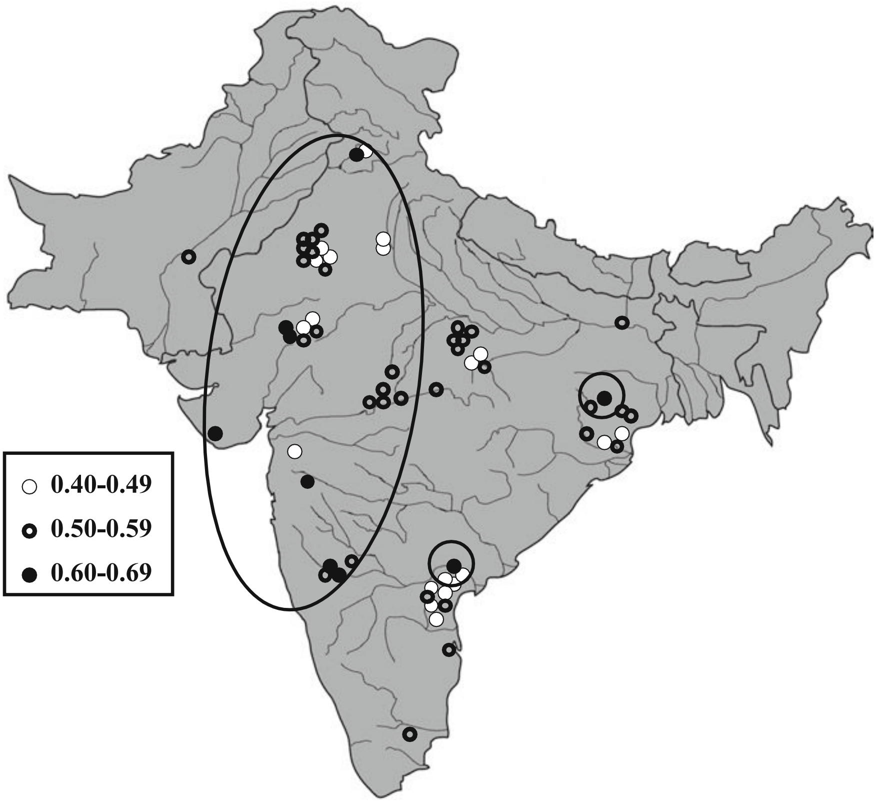

Fig. 6.7 Locational map showing the distribution of the handaxe assemblages across the Indian subcontinent based only on mean refinement values

largest and least refined specimens. This clearly hints at the considerable metric diversity of these assemblages. Instead of discussing the individual results for each group of handaxe assemblages, the most salient observations are presented below for the most relevant or representative groups in the context of wider implications for the South Asian Acheulean. Most of these published assemblages come from surface contexts and very few derive from stratified contexts. Raw material type and quality were not considered as causal factors for metric variability in this study because the majority of specimens were manufactured on quartzite clasts.

Results of Ranking Exercise: Question 1

As noted above, previous investigators have often variably separated the South Asian bifaces assemblages into Early and Late Acheulean technological stages based primarily on length, elongation and refinement. Other attributes such as the number of flake scars and absolute or relative dates when available have also been occasionally utilized. Therefore, an important aim was to see where all known assemblages are situated in relation to each other when values for each of the five variables are sequentially sorted. This simple exercise revealed three important observations that have critical implications on how the South Asian Acheulean evidence is interpreted.

(a) Instead of separating into two distinguishable groups (i.e., Early vs. Late Acheulean) when sorted, there is a broadly continuous range of metric values for all five variables. Some sites previously thought to be Early or Late Acheulean, based on their metrical values alone, actually end up in the middle of the sorted list. The interassemblage cluster analysis (results discussed later) further reinforced this observation.
(b) Assemblages that were sequentially close to one another in one unilinear variable (e.g., length) did *not always* rank proportionately or similarly in other unilinear variable(s) (e.g., breadth, thickness).
(c) Similarly, elongation and refinement values, though respectively dependent on the unilinear values, did not consistently display a significant and consistent relationship with them. Indeed, there appears to be significant *and respective* variation in size, elongation, and refinement within the South Asian Acheulean handaxe record.

Results of the Inter-assemblage Comparisons (Hierarchical Cluster Analyses): Question 2

In order to compare individual assemblages with each other, three separate dendrograms were generated using the “between-groups” linkage cluster method at a Euclidean distance interval through three different combinations of the five main attributes: (1) length, breadth, thickness (Fig. 6.8); (2) elongation and refinement (Fig. 6.9);

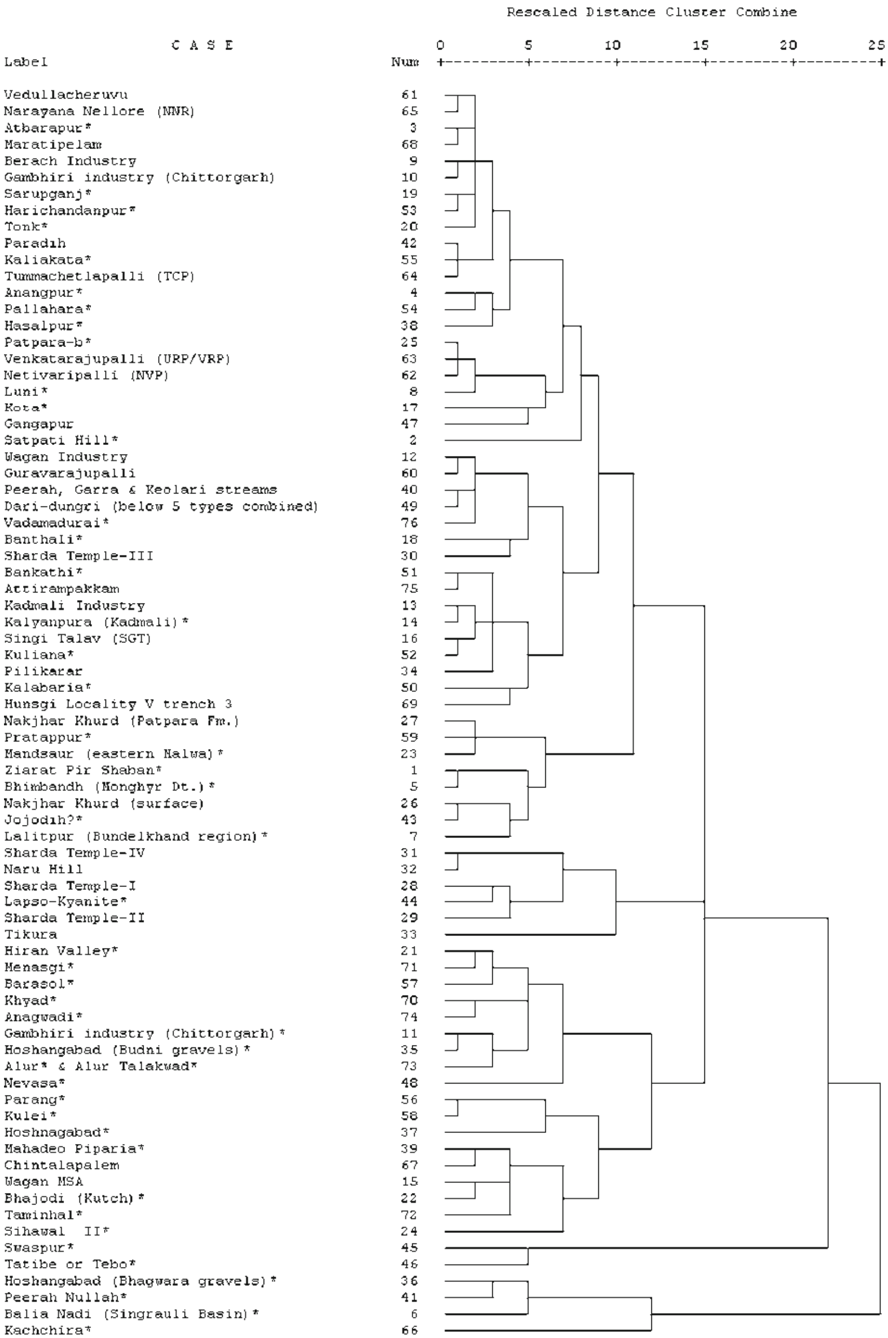

Fig. 6.8 Dendrogram generated from the cluster analysis using length, breadth and thickness values (108 assemblages)

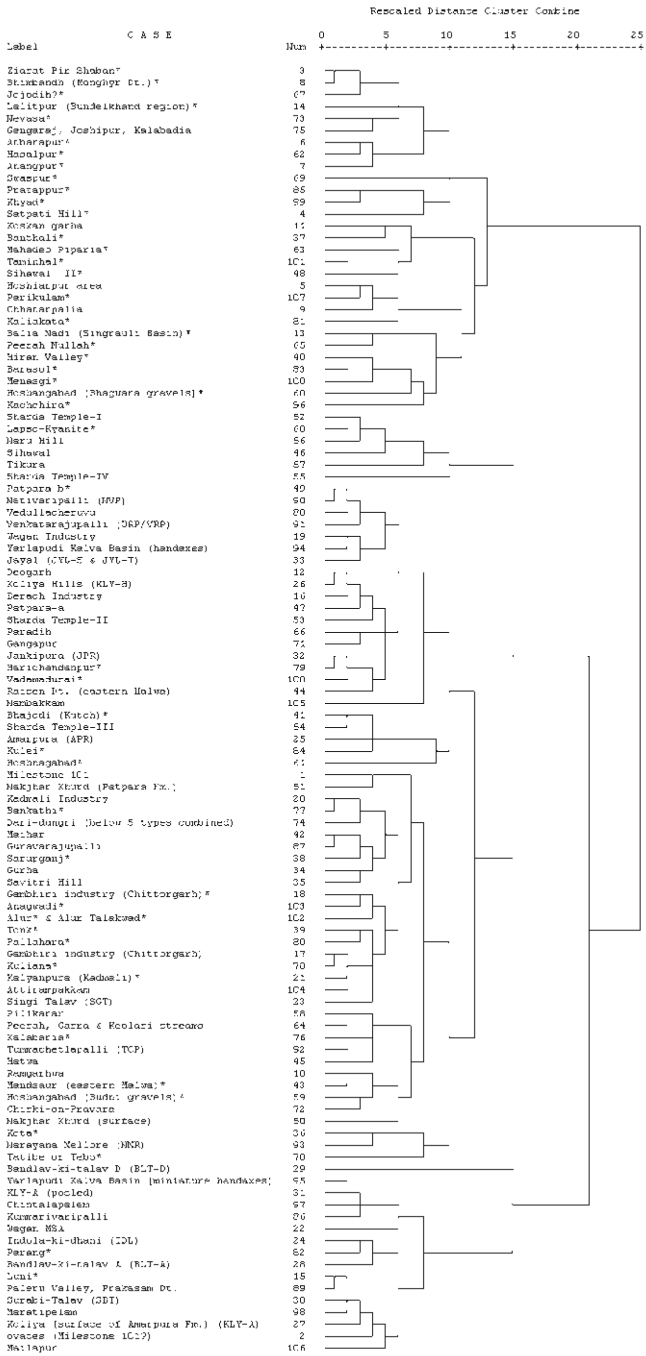

Fig. 6.9 Dendrogram generated from the cluster analysis using elongation and refinement values (76 assemblages)

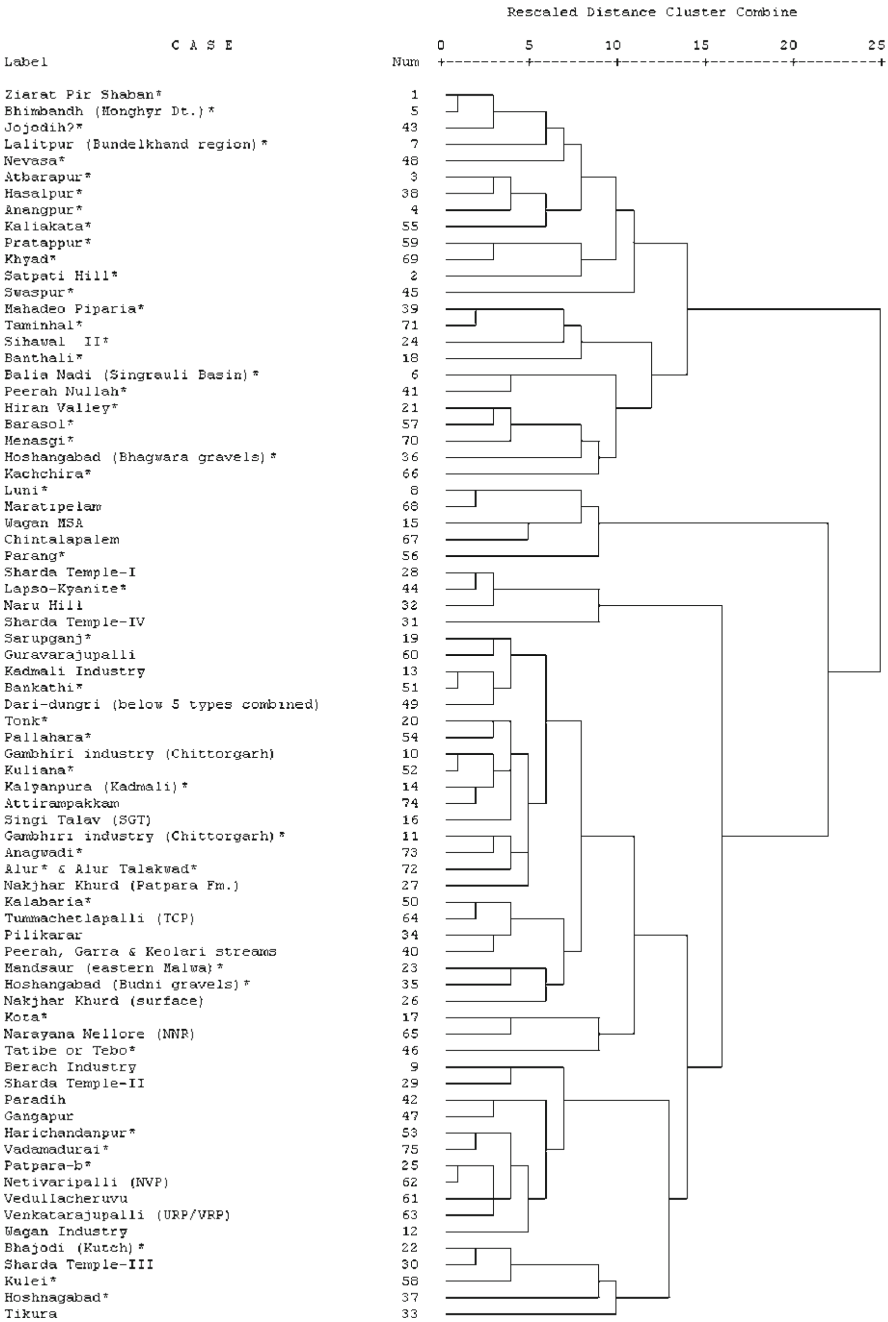

Fig. 6.10 Dendrogram generated from the cluster analysis using the values of all five variables together (length, breadth, thickness, elongation and refinement; 75 assemblages)

and (3) all five of these attributes combined (Fig. 6.10). This type of analysis has been done for the first time for South Asian handaxe assemblages and its main purpose was to address Question 2.

All three dendrograms resulted in the formation of multiple handaxe groups. In all three analyses, individual assemblages clustered in varying patterns respectively and moreover, multiple assemblages that came from the same site/locality/area did not consistently cluster together in any of the three dendrograms as expected. Although some of these single-locality or single-region assemblages clustered relatively close to each other in one dendrogram (e.g. Hoshangabad and Peerah Nullah at bottom of Fig. 6.9), they were found to rank far apart from each other in the other dendrograms. For example, handaxe assemblages from the Didwana group (e.g. Singi Talav, Indola-ki-dhani, Amarpura) are thought to be Early Acheulean and broadly contemporaneous with each other. Nevertheless, all Didwana assemblages are respectively scattered across the dendrogram and separately cluster with other handaxe assemblages found throughout the subcontinent (see Fig. 6.8). In addition, almost none of these variables (length, breadth, thickness, elongation and refinement) result in the separate clustering of Early and Late Acheulean assemblages. This is evident in all three dendrograms, where such assemblages as Chirki-on-Pravara, Nevasa and Anagwadi (all typologically and chronologically Early Acheulean) variably cluster closer with such assemblages as Nakjhar Khurd, Gambhiri and Kalyanpura (all typologically Late Acheulean).

There are several possible explanations for this unexpected phenomenon regarding the variation in clustering between different handaxe assemblages:

(a) South Asian handaxe assemblages that have been previously interpreted as Early or Late Acheulean, respectively, based on their primary metric values, have been misclassified based on insufficient evidence.
(b) South Asian handaxe assemblages (and the Acheulean in general) possess a larger range of morphological and metric diversity than previously acknowledged. Many of these assemblages probably represent regional (i.e., South Asian) development of the Acheulean after its initial dispersal into the subcontinent. As a result, they may not always fall strictly into one of two discrete types (Early vs. Late).
(c) Finally, the generated dendrograms, combined with a large portion of the intergroup comparisons (discussed below) indicate that there is significant geographic overlap between different types of assemblages. Both Early and Late Acheulean sites occur throughout most of the Indian subcontinent and thus, sites that are often farther apart cluster together

All of these points outlined above collectively imply that handaxe assemblages of varying dimensions and morphologies occur throughout the entire subcontinent, possibly a result of increasingly intense intraregional Acheulean dispersal and occupation during the Middle Pleistocene. Additionally, some of the published specimens may represent incomplete handaxes, provisionally explaining the mixed clustering of Early and Late assemblages. On the other hand, there still appears to be some broad or tentative patterning with some of the sites but not all. For example, out of 24 sites that cluster together based on the five variables (at the top

of Fig. 6.10), only two of these are from southern India. The remaining 22 are all from the northern half of the subcontinent. When grouped according to the three linear variables (Fig. 6.8), all of the same 24 sites cluster together again in the same group (albeit with – despite a difference of 33 assemblages between the two dendrograms). When observing the 75 sites from all five variables, five or six broad groups can be arbitrarily distinguished (Fig. 6.10). Except for Gangapur – which has been interpreted as Early Acheulean in the past – the remaining 16 assemblages in the fifth group all appear to be Late Acheulean. The two of the smallest groups of five and four assemblages respectively, also comprise primarily Late Acheulean assemblages: (1) Luni, Maratipelam, Wagan, Chintalapelam, Parang and (2) Sharda Temple-I, Lapso-Kyanite, Naru Hill, and Sharda Temple-IV. Likewise, three of the (previously recognized) Early Acheulean assemblages (Pilikarar, Anagwadi, Singi Talav) cluster in one group, but the other 23 assemblages in that same group appear to represent primarily Late Acheulean types (e.g. Kadmali Industry, Gambhiri Industry, Nakjhar Khurd). This may indicate metrical overlap between all of these assemblages, but at the same time, questions the current universal validity of Acheulean bifaces becoming more refined over time. While there was, no doubt, a lengthy technomorphological progression over time, these changing trends were probably: (1) extremely protracted and subtle over both time and space; (2) inconsistent at a multi-geographic level; and (3) probably often reversed depending on internal and external influences and a multitude of factors. The results of the three cluster analyses are also varied depending on the combinations of the variables used. For example, when grouped according to elongation and refinement, Sharda Temple-I, II, and IV cluster together; but only Sharda Temple-I and IV cluster together when grouped according to length–width–thickness and also when using all five variables. The assemblage from Sharda Temple-III was consistently in different groups in all three dendrograms.

From the preliminary results presented here, it is not yet possible to provide a definitive answer to Question 2. This, in itself highlights the importance of and the direction that future work in the region needs to take. As more comprehensive data and a larger number of attributes and variables are factored in from more sites in the future, a more accurate pattern of grouping should be evident between techno-chronologically separate biface assemblages. For the time being, all three tentative dendrograms generated in this paper are useful as a comparative source of reference to see which individual assemblages are most closely similar to each other based on given metric variables.

Results of the Inter-group Comparisons (Mann–Whitney *U*-tests): Question 3

In order to metrically compare groups of assemblages at an inter-regional level, the Mann–Whitney *U*-test was utilized on all compiled handaxe assemblages. This exercise was carried out separately for each of the five variables and revealed the

statistical levels of difference between regional groups of handaxe assemblages (Tables 6.2–6.6). For example, the Berach group, which comprises seven assemblages, is not statistically different from the Satna Dt. and the Tamil Nadu groups ($p=1.00$ for both). However, the Berach group is statistically different from the Narmada West ($p=0.01$) and Karnataka groups ($p=0.03$), which, not surprisingly, are not statistically different from each other ($p=0.73$). One of the most interesting results for the length variable was of the Didwana group comprised of 11 assemblages in the Thar Desert. It is statistically different from 17 of the 28 groups (see Table 6.2). This may be the result of differences in sample size when compared with other groups or it may signify that the Didwana group is highly diverse and unique in comparison to most other South Asian assemblages. The latter possibility is better supported since this assemblage is also statistically different with 12 and 10 other groups regarding breadth and thickness respectively. As statistically different as the Didwana group is to most other South Asian assemblages, six groups (Delhi, Uttar Pradesh, Malwa, Gujarat, Orissa 2 and Andhra 4) basically show the opposite pattern. These six groups do not show statistical differences in length when compared with all other groups (with the exception of Didwana, of course and in the case of Gujarat, Andhra 3: $p=0.029$) including each other. In fact, the Andhra 4 group also does not appear to be statistically different from other the groups in terms of breadth, thickness, and elongation and is statistically different in only refinement with the Didwana and Orissa 3 groups.

Regarding thickness, the Satna group shows a pattern similar to that of Didwana for length in that it is statistically different from seven other groups as demonstrated by the p values in Table 6.4. Regarding elongation, the Satna group has the highest frequency of significant statistical differences with 12 other groups. After Satna, Karnataka is the second most different group regarding elongation as it is statistically different from 7 other groups. Finally, an example in relation to the refinement attribute is demonstrated by two groups, Jharkhand 2 and Andhra 2 ($p=0.73$). Interestingly, they both displayed significant statistical differences each with the *same* 11 groups: Berach Valley, Didwana region, C. Rajasthan, Gujarat, Satna Dt., Narmada west, Narmada east, Orissa 1, Orissa 3, Karnataka and Tamil Nadu. There does not appear to be any geographic overlap or a visible pattern with the other differing groups. The Andhra 4 group shows no statistical differences with other groups in regards to length, breadth, thickness, and elongation, but shows a statistical difference in refinement with the Didwana ($p=0.026$) and Orissa 3 ($p=0.044$) groups.

As mentioned previously, the Didwana assemblages show the statistically greatest differences regarding length, breadth and thickness. Elongation and refinement values were not available for the Milestone locality in Pakistan and the Belan Valley in northern India so those assemblages were not included in that analysis. Nonetheless, what this basic study broadly illustrates is that except for the Andhra 4 group in southern India, the nine groups that are not statistically different with other groups including each other, are located in northern and central India. What this may indirectly imply is that they include handaxe assemblages with metric values that fall within an intermediate range. An alternate or additional explanation

Table 6.2 Inter-group *Mann–Whitney U*-test results for the length variable [upper diagonal numbers indicate Mann–Whitney *U*-values

	Milestone 101	Satpati and Bhimbandh	Hoshiarpur area	Delhi area	Belan Valley	U.P. area	W. Rajasthan	Berach Valley	Didwana region	E. Rajasthan	C. Rajasthan	Gujarat	E. Malwa
Milestone 101	–	0.000	0.000	1.000	0.000	1.000	3.000	6.000	5.000	2.000	3.000	3.000	2.000
Satpati and Bhimbandh	0.333	–	0.000	1.000	0.000	1.000	0.500	0.000	0.000	0.000	0.000	0.000	0.000
Hoshiarpur area	0.333	0.333	–	2.000	2.000	2.000	2.000	0.000	0.000	2.000	1.000	1.000	0.000
Delhi area	0.667	0.667	1.000	–	3.000	3.000	1.000	2.000	0.000	2.000	1.000	1.000	1.000
Belan Valley	0.200	0.200	0.800	1.000	–	3.000	3.000	0.000	0.000	3.000	2.000	2.000	1.000
U.P. area	0.400	0.400	0.800	1.000	0.700	–	2.000	4.000	2.500	4.000	3.000	2.000	2.000
W. Rajasthan	1.000	0.200	0.800	0.400	0.700	0.400	–	10.000	11.000	4.000	4.000	4.000	3.000
Berach Valley	0.889	0.056	0.056	0.222	0.017	0.183	1.000	–	19.000	8.000	10.000	14.000	8.000
Didwana region	0.308	0.026	0.026	0.026	0.005	0.022	0.456	0.085	–	2.000	5.000	8.000	4.000
E. Rajasthan	0.533	0.133	0.533	0.533	0.400	0.629	0.629	0.315	0.006	–	6.000	3.000	5.000
C. Rajasthan	0.800	0.133	0.267	0.267	0.229	0.400	0.629	0.527	0.026	0.686	–	6.000	6.000
Gujarat	0.800	0.133	0.267	0.267	0.229	0.229	0.629	1.000	0.078	0.200	0.686	–	5.000
E. Malwa	0.800	0.200	0.200	0.400	0.200	0.400	0.700	0.667	0.060	0.857	1.000	0.857	–
Son Valley	0.267	0.089	0.267	0.711	0.133	0.376	0.376	0.152	0.003	0.933	0.683	0.570	0.776
Satna Dt.	0.889	0.056	0.056	0.111	0.017	0.183	0.517	1.000	0.020	0.315	0.648	0.788	0.517
Narmada west	0.143	0.071	0.643	0.857	0.714	0.548	0.714	0.035	0.003	0.476	0.352	0.476	0.262
Narmada east	0.133	0.133	0.800	1.000	0.400	0.857	0.629	0.006	0.001	0.114	0.057	0.057	0.114
Jharkhand 1	0.667	0.333	0.333	0.333	0.200	0.400	0.800	0.333	1.000	0.133	0.267	0.533	0.400
Jharkhand 2	0.190	0.571	0.857	0.571	0.786	0.786	0.143	0.030	0.000	0.111	0.111	0.063	0.250
Maharashtra	0.533	0.133	0.533	0.533	0.400	0.857	0.629	0.164	0.006	0.886	0.486	0.343	0.629
Orissa 1	0.381	0.190	0.571	0.857	0.571	0.786	0.393	0.073	0.002	0.730	0.730	0.190	0.571
Orissa 2	0.333	0.333	0.667	1.000	0.800	0.800	0.800	0.111	0.026	0.533	0.267	0.267	0.400
Orissa 3	0.711	0.089	0.400	0.400	0.376	0.376	0.630	0.463	0.016	0.570	1.000	0.683	0.775
Andhra 1	0.533	0.133	0.133	0.133	0.057	0.114	0.629	0.315	0.949	0.057	0.114	0.343	0.114
Andhra 2	0.533	0.133	0.133	0.533	0.057	0.229	0.857	0.788	0.780	0.486	0.686	0.886	0.629
Andhra 3	0.267	0.133	0.133	0.133	0.057	0.057	0.229	0.042	0.343	0.029	0.029	0.029	0.057
Andhra 4	1.000	0.333	0.667	0.667	0.800	0.400	1.000	0.889	0.410	0.800	0.800	0.800	1.000
Karnataka	0.111	0.111	0.667	1.000	0.517	1.000	0.383	0.011	0.000	0.230	0.164	0.109	0.267

and the lower diagonal numbers indicate the corresponding p-values (exact significance [2 × one-tailed significance])]

Son Valley	Satna Dt.	Narmada west	Narmada east	Jharkhand 1	Jharkhand 2	Maharashtra	Orissa 1	Orissa 2	Orissa 3	Andhra 1	Andhra 2	Andhra 3	Andhra 4	Karnataka	Tamil Nadu
3.000	6.000	1.000	0.000	1.000	1.000	2.000	2.000	0.000	6.000	2.000	2.000	1.000	2.000	1.000	7.000
1.000	0.000	0.000	0.000	0.000	3.000	0.000	1.000	0.000	1.000	0.000	0.000	0.000	0.000	1.000	2.000
3.000	0.000	4.000	3.000	0.000	4.000	2.000	3.000	1.000	4.000	0.000	0.000	0.000	1.000	5.000	2.000
6.000	1.000	5.000	4.000	0.000	3.000	2.000	4.000	2.000	4.000	0.000	2.000	0.000	1.000	7.000	4.000
4.000	0.000	7.000	3.000	0.000	6.000	3.000	5.000	2.000	7.000	0.000	0.000	0.000	2.000	7.000	4.000
7.000	4.000	6.000	5.000	1.000	6.000	5.000	6.000	2.000	7.500	1.000	2.000	0.000	1.000	10.000	5.500
7.000	7.000	7.000	4.000	2.000	2.000	4.000	4.000	2.000	9.000	4.000	5.000	2.000	3.000	6.000	10.000
15.000	24.000	6.000	0.000	3.000	4.000	6.000	6.000	1.000	21.000	8.000	12.000	3.000	6.000	5.500	28.000
9.000	13.000	5.000	0.000	11.000	0.000	2.000	2.000	0.000	15.500	21.000	8.000	14.000	6.000	1.000	24.500
15.000	8.000	8.000	2.000	0.000	3.000	7.000	8.000	2.000	12.000	1.000	5.000	0.000	3.000	7.000	9.000
13.000	11.000	7.500	1.000	1.000	3.000	5.000	8.000	1.000	16.000	2.000	6.000	0.000	3.000	6.000	12.000
12.000	12.000	8.000	1.000	2.000	2.000	4.000	4.000	1.000	13.000	4.000	7.000	0.000	3.000	5.000	14.000
10.000	7.000	4.000	1.000	1.000	3.000	4.000	5.000	1.000	10.500	1.000	4.000	0.000	3.000	5.000	10.000
–	19.000	15.000	5.000	2.000	8.000	14.000	15.500	4.000	30.000	3.000	10.000	0.000	7.000	19.000	21.000
0.336	–	7.000	0.500	3.000	2.500	5.000	9.000	1.000	22.000	3.000	12.000	0.000	7.000	5.000	24.500
0.282	0.051	–	8.000	1.000	10.000	10.000	13.000	6.000	19.000	2.000	4.000	1.000	4.000	18.000	13.000
0.073	0.006	0.476	–	0.000	8.000	5.000	5.000	1.000	6.000	0.000	0.000	0.000	1.000	9.000	5.000
0.178	0.333	0.143	0.133	–	0.000	1.000	0.000	0.000	3.000	3.000	2.000	3.000	1.000	0.000	5.000
0.093	0.010	0.429	0.730	0.095	–	5.000	6.000	4.000	10.000	0.000	3.000	0.000	2.000	13.000	8.000
0.808	0.109	0.762	0.486	0.267	0.286	–	9.000	3.000	12.000	1.000	4.000	0.000	3.000	11.000	9.000
0.524	0.202	0.792	0.286	0.095	0.222	0.905	–	4.000	15.000	2.000	5.000	0.000	4.000	15.000	10.000
0.400	0.111	1.000	0.267	0.333	0.857	0.800	0.857	–	4.000	0.000	1.000	0.000	1.000	7.000	3.000
0.878	0.536	0.573	0.109	0.267	0.171	0.570	0.524	0.400	–	6.000	12.000	2.000	6.000	18.000	24.500
0.028	0.042	0.038	0.029	0.800	0.016	0.057	0.063	0.133	0.109	–	3.000	5.000	2.000	0.000	8.000
0.368	0.788	0.114	0.029	0.533	0.111	0.343	0.286	0.267	0.570	0.200	–	0.000	4.000	6.000	15.000
0.004	0.006	0.019	0.029	0.800	0.016	0.029	0.016	0.133	0.016	0.486	0.029	–	2.000	0.000	3.000
0.889	1.000	0.643	0.267	0.667	0.381	0.800	0.857	0.667	0.711	0.533	1.000	0.533	–	5.000	8.000
0.336	0.011	0.731	0.412	0.056	0.530	0.648	0.755	1.000	0.281	0.006	0.164	0.006	0.667	–	13.000
0.279	0.694	0.181	0.073	0.533	0.093	0.283	0.171	0.267	0.442	0.214	0.933	0.028	1.000	0.094	–

Table 6.3 Inter-group *Mann–Whitney U*-test results for the breadth variable [upper diagonal numbers indicate Mann–Whitney

	Milestone 101	Satpati and Bhimbandh	Hoshiarpur area	Delhi area	Belan Valley	U.P. area	W. Rajasthan	Berach Valley	Didwana region	E. Rajasthan	C. Rajasthan	Gujarat	E. Malwa	Son Valley
Milestone 101	–	0.000	0.000	0.000	0.000	0.000	2.000	4.000	10.000	0.000	2.000	2.000	0.000	0.000
Satpati and Bhimbandh	0.333	–	2.000	1.000	3.000	0.000	0.500	0.000	0.000	1.000	2.000	0.000	0.000	1.000
Hoshiarpur area	0.333	1.000	–	2.000	3.000	0.000	0.000	0.000	0.000	1.000	2.000	0.000	0.000	2.000
Delhi area	0.333	0.667	1.000	–	3.000	1.000	1.000	0.000	1.000	2.000	2.000	2.000	0.000	3.000
Belan Valley	0.200	1.000	1.000	1.000	–	3.000	1.000	3.500	3.000	4.000	4.000	3.000	1.500	6.000
U.P. area	0.200	0.200	0.200	0.400	0.700	–	3.000	3.000	4.000	4.000	5.500	5.000	0.000	9.000
W. Rajasthan	0.800	0.200	0.200	0.400	0.200	0.700	–	9.000	15.000	3.000	3.000	5.000	2.000	7.000
Berach Valley	0.500	0.056	0.056	0.056	0.117	0.117	0.330	–	28.000	3.000	5.000	6.500	6.500	21.000
Didwana region	0.923	0.026	0.026	0.051	0.038	0.060	0.885	0.375	–	3.000	9.000	10.000	5.000	18.000
E. Rajasthan	0.133	0.267	0.267	0.533	0.629	0.629	0.400	0.042	0.010	–	6.000	6.500	0.000	10.500
C. Rajasthan	0.533	0.533	0.533	0.533	0.629	0.857	0.400	0.109	0.104	0.686	–	7.000	2.000	14.000
Gujarat	0.533	0.133	0.133	0.533	0.400	0.857	0.857	0.164	0.138	0.686	0.886	–	2.000	15.500
E. Malwa	0.333	0.333	0.333	0.333	0.400	0.200	0.800	0.889	0.308	0.133	0.533	0.533	–	7.000
Son Valley	0.044	0.089	0.178	0.267	0.279	0.630	0.376	0.463	0.033	0.368	0.808	0.933	0.889	–
Satna Dt.	0.056	0.500	0.889	0.889	1.000	0.117	0.117	0.001	0.000	0.164	0.230	0.164	0.056	0.072
Narmada west	0.071	0.286	0.643	0.429	0.905	1.000	0.262	0.101	0.007	0.762	1.000	0.914	0.143	0.491
Narmada east	0.133	0.267	0.533	1.000	0.857	0.229	0.400	0.006	0.006	0.486	0.343	0.343	0.133	0.214
Jharkhand 1	1.000	0.333	0.333	0.333	0.200	0.200	1.000	0.500	0.769	0.133	0.267	0.267	0.333	0.267
Jharkhand 2	0.095	0.190	0.381	0.857	0.571	0.393	0.393	0.048	0.005	0.730	0.556	0.286	0.381	0.222
Maharashtra	0.133	0.133	0.133	0.267	0.229	0.629	0.629	0.527	0.104	0.200	0.886	0.686	1.000	0.933
Orissa 1	0.095	0.095	0.095	0.571	0.393	1.000	0.571	0.106	0.027	0.556	0.905	1.000	0.571	0.833
Orissa 2	0.333	0.667	1.000	0.667	1.000	0.800	0.400	0.111	0.103	0.800	1.000	0.800	0.333	0.400
Orissa 3	0.178	0.178	0.089	0.533	0.376	0.776	0.279	0.054	0.016	0.808	0.933	0.808	0.400	0.645
Andhra 1	0.800	0.133	0.133	0.267	0.114	0.229	0.857	0.648	0.851	0.114	0.343	0.343	0.533	0.073
Andhra 2	0.133	0.133	0.133	0.533	0.229	0.629	0.629	0.412	0.138	0.343	1.000	0.686	1.000	0.683
Andhra 3	0.533	0.133	0.133	0.133	0.057	0.057	0.400	0.109	0.226	0.029	0.057	0.114	0.133	0.016
Andhra 4	1.000	0.333	0.333	0.667	0.400	1.000	0.800	1.000	1.000	0.800	0.800	1.000	1.000	0.711
Karnataka	0.429	0.286	0.429	0.429	0.262	0.905	0.262	0.445	0.048	0.610	0.914	0.914	1.000	0.852
Tamil Nadu	0.400	0.178	0.267	0.267	0.194	0.630	0.497	0.536	0.206	0.461	0.683	0.933	1.000	0.721

U-values and the lower diagonal numbers indicate the corresponding *p*-values (exact significance [2×one-tailed significance])]

Satna Dt.	Narmada west	Narmada east	Jharkhand 1	Jharkhand 2	Maharashtra	Orissa 1	Orissa 2	Orissa 3	Andhra 1	Andhra 2	Andhra 3	Andhra 4	Karnataka	Tamil Nadu
0.000	0.000	0.000	2.000	0.000	0.000	0.000	0.000	2.000	3.000	0.000	2.000	2.000	3.000	4.000
4.500	2.000	1.000	0.000	1.000	0.000	0.000	1.000	2.000	0.000	0.000	0.000	0.000	2.000	2.000
6.000	4.000	2.000	0.000	2.000	0.000	0.000	2.000	1.000	0.000	0.000	0.000	0.000	3.000	3.000
6.000	3.000	4.000	0.000	4.000	1.000	3.000	1.000	5.000	1.000	2.000	0.000	1.000	3.000	3.000
10.000	8.000	5.000	0.500	5.000	2.000	4.000	3.000	7.000	1.000	2.000	0.000	1.000	4.000	5.000
3.000	9.000	2.000	0.000	4.000	4.500	7.000	2.000	10.000	2.000	4.000	0.000	3.000	8.000	9.000
3.000	4.000	3.000	3.000	4.000	4.000	5.000	1.000	6.000	5.000	4.000	3.000	2.000	4.000	8.000
0.000	9.000	0.000	4.500	5.000	10.000	7.000	1.000	11.500	11.000	9.000	5.000	7.000	15.500	22.000
3.000	7.000	2.000	9.000	4.000	9.000	8.000	2.000	15.000	20.000	10.000	12.000	11.000	13.000	28.000
6.000	10.000	5.000	0.000	8.000	3.500	7.000	3.000	14.000	2.000	4.000	0.000	3.000	9.000	11.000
7.000	12.000	4.000	1.000	7.000	7.500	9.000	4.000	15.000	4.000	8.000	1.000	3.000	11.000	13.000
6.000	11.000	4.000	1.000	5.000	6.500	10.000	3.000	14.500	4.000	6.000	2.000	4.000	11.000	15.000
0.000	1.000	0.000	0.500	2.000	4.000	3.000	0.000	4.000	2.000	4.000	0.000	2.000	6.000	8.000
12.000	18.000	8.000	3.000	11.500	15.500	18.000	4.000	27.500	5.000	13.000	2.000	6.500	22.000	28.500
–	14.000	13.000	0.000	15.000	3.000	8.000	6.000	12.000	1.500	6.000	0.000	3.000	12.000	12.000
0.366	–	9.000	0.000	13.500	7.000	10.000	3.000	21.000	3.000	6.000	0.000	4.000	13.000	16.000
0.927	0.610	–	0.000	9.000	2.000	4.000	4.000	10.000	1.000	4.000	0.000	2.000	9.000	9.000
0.056	0.071	0.133	–	1.000	2.000	1.000	0.000	2.000	4.000	2.000	2.000	2.000	3.000	5.000
0.755	0.792	0.905	0.190	–	4.000	6.000	4.000	13.000	1.000	3.500	0.000	2.500	11.000	12.000
0.042	0.352	0.114	0.533	0.190	–	6.000	2.000	12.000	3.000	8.000	0.000	4.000	12.000	14.000
0.149	0.429	0.190	0.190	0.222	0.413	–	3.000	20.000	2.000	9.000	0.000	5.000	14.000	16.000
0.889	0.429	1.000	0.333	0.857	0.533	0.571	–	6.000	1.000	2.000	0.000	1.000	3.000	4.000
0.072	0.755	0.368	0.178	0.354	0.570	1.000	0.711	–	6.000	13.000	1.000	6.000	24.000	26.000
0.012	0.067	0.057	1.000	0.032	0.200	0.063	0.267	0.109	–	2.000	4.000	4.000	4.000	10.000
0.164	0.257	0.343	0.533	0.111	1.000	0.905	0.533	0.683	0.114	–	1.000	4.000	11.000	16.000
0.006	0.010	0.029	0.533	0.016	0.029	0.016	0.133	0.008	0.343	0.057	–	4.000	2.000	4.000
0.330	0.643	0.533	1.000	0.381	1.000	1.000	0.667	0.711	1.000	1.000	1.000	–	4.000	6.000
0.234	0.485	0.610	0.429	0.537	1.000	0.931	0.429	1.000	0.114	0.914	0.038	0.643	–	13.000
0.072	0.345	0.283	0.533	0.284	0.808	0.622	0.400	0.574	0.368	1.000	0.048	0.711	0.755	–

Table 6.4 Inter-group *Mann–Whitney* *U*-test results for the thickness variable [upper diagonal numbers indicate Mann–Whitney

	Milestone 101	Satpati and Bhimbandh	Hoshiarpur area	Delhi area	Belan Valley	U.P. area	W. Rajasthan	Berach Valley	Didwana region	E. Rajasthan	C. Rajasthan	Gujarat	E. Malwa	Son Valley
Milestone 101	–	0.000	0.000	0.000	0.000	0.000	2.000	0.000	5.000	1.000	0.000	1.000	0.000	1.000
Satpati and Bhimbandh	0.333	–	2.000	2.000	2.000	2.000	0.500	2.000	0.000	2.000	2.000	2.000	0.000	4.000
Hoshiarpur area	0.333	1.000	–	1.000	2.000	2.000	1.000	1.500	0.000	2.000	2.000	2.000	0.000	4.000
Delhi area	0.333	1.000	0.667	–	1.000	2.000	1.000	7.000	7.500	2.000	3.000	2.000	3.000	7.000
Belan Valley	0.200	0.800	0.800	0.400	–	3.000	1.000	3.500	1.000	4.000	3.000	5.000	0.000	5.000
U.P. area	0.200	0.800	0.800	0.800	0.700	–	2.000	9.000	6.000	6.000	6.000	6.000	3.000	10.000
W. Rajasthan	0.800	0.200	0.400	0.400	0.200	0.400	–	6.000	12.000	1.000	3.000	1.000	3.000	6.000
Berach Valley	0.056	0.222	0.111	1.000	0.117	0.833	0.383	–	19.000	7.000	13.000	7.000	9.000	25.000
Didwana region	0.308	0.026	0.026	0.513	0.011	0.126	0.555	0.085	–	8.000	8.000	9.000	6.000	29.000
E. Rajasthan	0.267	0.533	0.533	0.533	0.629	1.000	0.114	0.230	0.078	–	7.000	7.000	3.000	13.000
C. Rajasthan	0.133	0.533	0.533	0.800	0.400	1.000	0.400	0.927	0.078	0.886	–	7.000	3.000	14.000
Gujarat	0.267	0.533	0.533	0.533	0.857	1.000	0.114	0.230	0.104	0.886	0.886	–	3.000	12.000
E. Malwa	0.200	0.200	0.200	1.000	0.100	0.700	0.700	0.833	0.126	0.400	0.400	0.400	–	8.000
Son Valley	0.089	0.400	0.400	0.889	0.194	0.776	0.279	0.779	0.238	0.683	0.808	0.570	0.497	–
Satna Dt.	0.056	0.500	0.500	0.222	1.000	0.667	0.067	0.026	0.000	0.527	0.315	0.927	0.117	0.121
Narmada west	0.071	0.286	0.286	0.143	0.714	0.381	0.048	0.008	0.000	0.610	0.171	0.610	0.024	0.043
Narmada east	0.133	0.133	0.267	0.267	0.629	0.400	0.057	0.012	0.001	0.486	0.200	0.486	0.057	0.109
Jharkhand 1	0.667	0.333	0.333	0.667	0.200	0.200	0.800	0.111	0.410	0.267	0.133	0.267	0.200	0.089
Jharkhand 2	0.571	0.381	0.381	0.857	0.143	0.393	0.786	0.432	0.827	0.111	0.413	0.190	0.786	0.622
Maharashtra	0.267	0.533	0.533	0.533	0.400	1.000	0.114	0.230	0.078	0.200	0.886	0.343	0.400	0.683
Orissa 1	0.095	0.381	0.381	0.857	0.250	0.786	0.393	0.639	0.013	0.286	0.556	0.286	0.571	0.354
Orissa 2	0.333	1.000	0.667	0.667	1.000	0.800	0.400	0.111	0.026	0.800	0.533	1.000	0.200	0.400
Orissa 3	0.044	0.711	0.711	0.533	0.630	0.776	0.194	0.397	0.016	0.933	0.933	0.933	0.630	0.382
Andhra 1	0.800	0.133	0.133	0.267	0.114	0.229	0.629	0.109	0.571	0.114	0.200	0.200	0.400	0.214
Andhra 2	1.000	0.133	0.133	0.267	0.057	0.229	0.857	0.042	0.412	0.057	0.200	0.057	0.400	0.109
Andhra 3	0.533	0.133	0.133	0.267	0.057	0.057	1.000	0.240	0.138	0.057	0.057	0.057	0.057	0.028
Andhra 4	0.667	1.000	1.000	1.000	1.000	1.000	0.400	1.000	0.641	1.000	1.000	0.800	1.000	1.000
Karnataka	0.071	1.000	0.857	0.429	1.000	0.548	0.167	0.073	0.001	0.610	0.352	0.914	0.167	0.108

U-values and the lower diagonal numbers indicate the corresponding *p*-values (exact significance [2×one-tailed significance])]

Satna Dt.	Narmada west	Narmada east	Jharkhand 1	Jharkhand 2	Maharashtra	Orissa 1	Orissa 2	Orissa 3	Andhra 1	Andhra 2	Andhra 3	Andhra 4	Karnataka	Tamil Nadu
0.000	0.000	0.000	1.500	3.000	1.000	0.000	0.000	0.000	3.000	4.000	2.500	1.000	0.000	6.000
4.000	2.000	0.500	0.000	2.000	2.000	2.000	2.000	6.000	0.000	0.000	0.000	2.000	6.000	0.000
4.000	2.000	1.000	0.000	2.000	2.000	2.000	1.500	6.000	0.000	0.000	0.000	2.000	5.500	0.000
2.000	1.000	1.000	1.000	4.000	2.000	4.000	1.000	5.000	1.000	1.000	1.000	2.000	3.000	4.000
10.000	7.000	4.000	0.000	2.000	3.000	3.000	3.000	9.000	1.000	0.000	0.000	3.000	9.000	1.000
8.000	5.000	3.000	0.000	4.000	6.000	6.000	2.000	10.000	2.000	2.000	0.500	3.000	6.000	5.000
2.000	1.000	0.000	2.000	6.000	1.000	4.000	1.000	5.000	4.000	5.000	6.000	1.000	3.000	11.000
7.000	3.000	1.000	1.000	12.000	7.000	14.000	1.500	20.500	5.000	3.000	2.000	7.000	8.500	12.500
3.000	0.000	0.000	6.000	25.000	8.000	6.000	0.000	15.500	17.000	15.000	10.000	8.000	2.000	40.000
10.000	9.000	5.000	1.000	3.000	3.000	5.000	3.000	15.000	2.000	1.000	1.000	4.000	9.000	5.000
8.500	5.000	3.000	0.000	6.000	7.000	7.000	2.000	15.000	3.000	3.000	1.000	4.000	7.000	6.500
13.000	9.000	5.500	1.000	4.000	4.000	5.000	4.000	15.000	3.000	1.000	1.000	3.000	11.000	5.000
3.000	0.000	0.000	0.000	6.000	3.000	5.500	0.000	9.000	3.000	3.000	0.000	3.000	3.000	3.000
14.000	8.000	6.000	1.000	16.000	13.000	13.000	4.000	23.000	8.000	6.500	3.000	8.000	11.000	17.000
–	14.500	9.000	0.000	5.000	8.000	7.000	7.000	19.000	1.000	1.000	0.000	7.000	18.000	3.000
0.366	–	10.000	0.000	4.000	7.000	4.000	4.000	11.000	0.000	0.000	0.000	5.000	13.000	1.000
0.412	0.762	–	0.000	1.000	3.000	1.000	2.000	6.000	0.000	0.000	0.000	4.000	6.000	0.000
0.056	0.071	0.133	–	3.000	1.000	0.000	0.000	0.000	4.000	4.000	2.500	1.000	0.000	7.000
0.048	0.052	0.032	0.571	–	4.000	9.000	1.000	9.000	8.000	6.000	6.000	3.000	5.000	17.000
0.315	0.352	0.200	0.267	0.190	–	6.000	3.000	15.000	3.000	1.000	1.000	3.000	9.000	5.000
0.106	0.052	0.032	0.095	0.548	0.413	–	1.000	18.000	2.000	2.000	0.000	5.000	7.000	4.000
1.000	0.643	0.533	0.333	0.190	0.800	0.190	–	5.000	0.000	0.000	0.000	2.000	5.500	0.000
0.336	0.108	0.109	0.044	0.127	0.933	0.833	0.533	–	3.000	3.000	3.000	8.000	14.000	11.000
0.012	0.010	0.029	1.000	0.730	0.200	0.063	0.133	0.028	–	5.000	4.000	3.000	1.000	16.000
0.012	0.010	0.029	1.000	0.413	0.057	0.063	0.133	0.028	0.486	–	4.500	1.000	1.000	14.500
0.006	0.010	0.029	0.533	0.413	0.057	0.016	0.133	0.028	0.343	0.343	–	1.000	0.000	10.500
1.000	0.857	1.000	0.667	0.571	0.800	1.000	1.000	1.000	0.800	0.267	0.267	–	6.000	5.000
0.731	0.485	0.257	0.071	0.082	0.610	0.177	0.857	0.228	0.019	0.019	0.010	1.000	–	2.000
0.002	0.001	0.004	0.889	0.724	0.073	0.019	0.044	0.028	1.000	0.808	0.368	0.533	0.003	–

Table 6.5 Inter-group *Mann–Whitney U*-test results for the elongation variable [upper diagonal numbers indicate Mann–Whitney

	Milestone 101	Satpati and Bhimbandh	Hoshiarpur area	Delhi area	Belan Valley	U.P. area	W. Rajasthan	Berach Valley	Didwana region	E. Rajasthan	C. Rajasthan	Gujarat	E. Malwa	Son Valley
Milestone 101	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Satpati and Bhimbandh	–	–	0.000	0.000	–	0.000	2.500	1.500	0.000	0.000	0.000	0.500	0.000	4.000
Hoshiarpur area	–	0.667	–	0.500	–	0.000	1.000	3.000	0.000	1.000	1.500	2.000	0.000	1.000
Delhi area	–	0.333	0.667	–	–	0.000	2.000	5.000	0.000	2.000	2.000	4.000	0.000	3.000
Belan Valley	–	0.800	–	–	–	–	–	–	–	–	–	–	–	–
U.P. area	–	0.333	0.667	0.333	–	–	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W. Rajasthan	–	0.800	1.000	0.800	–	0.200	–	7.500	1.000	2.000	3.500	3.000	0.500	4.500
Berach Valley	–	0.111	1.000	0.667	–	0.056	0.517	–	1.000	6.500	12.500	12.000	0.000	8.500
Didwana region	–	0.667	1.000	0.667	–	0.667	1.000	0.500	–	0.500	0.000	2.000	0.000	2.000
E. Rajasthan	–	0.333	1.000	1.000	–	0.333	0.800	0.889	0.667	–	3.000	4.000	0.000	2.500
C. Rajasthan	–	0.133	0.800	0.533	–	0.133	0.400	0.788	0.400	0.800	–	7.000	0.000	4.000
Gujarat	–	0.133	1.000	1.000	–	0.133	0.400	0.788	1.000	1.000	0.886	–	0.000	4.000
E. Malwa	–	0.667	1.000	0.667	–	0.667	0.500	0.425	1.000	0.667	0.400	0.400	–	2.500
Son Valley	–	0.857	0.667	0.571	–	0.095	0.393	0.149	1.000	0.381	0.190	0.190	1.000	–
Satna Dt.	–	0.071	0.286	0.071	–	0.071	0.024	0.001	0.286	0.071	0.010	0.038	0.286	0.004
Narmada west	–	0.643	0.857	0.857	–	0.071	0.905	0.628	0.857	0.857	0.476	0.610	0.571	0.537
Narmada east	–	1.000	0.800	0.800	–	0.133	0.629	0.315	1.000	0.533	0.343	0.343	1.000	1.000
Jharkhand 1	–	0.333	1.000	0.667	–	0.333	0.400	0.500	0.667	0.667	0.800	0.800	0.667	0.190
Jharkhand 2	–	0.381	0.667	0.381	–	0.190	0.393	0.106	0.667	0.381	0.190	0.190	1.000	0.548
Maharashtra	–	0.800	1.000	1.000	–	0.800	1.000	1.000	1.000	1.000	0.629	0.857	1.000	0.786
Orissa 1	–	0.133	0.800	1.000	–	0.133	0.629	0.648	0.400	0.800	0.486	1.000	0.400	0.413
Orissa 2	–	0.333	1.000	1.000	–	0.333	0.800	0.889	0.667	1.000	0.800	1.000	0.667	0.381
Orissa 3	–	0.178	1.000	0.711	–	0.044	0.497	0.694	0.667	0.889	0.933	0.933	0.444	0.093
Andhra 1	–	0.333	0.667	0.333	–	0.333	0.800	0.667	0.667	0.667	0.533	1.000	0.667	0.190
Andhra 2	–	0.133	0.800	0.267	–	0.133	0.629	0.412	0.400	0.533	0.686	0.886	0.400	0.111
Andhra 3	–	0.333	1.000	0.667	–	0.333	0.800	0.889	0.667	1.000	0.800	1.000	0.670	0.381
Andhra 4	–	1.000	0.667	0.667	–	0.333	0.800	0.333	1.000	0.667	0.267	0.533	1.000	0.857
Karnataka	–	0.889	0.250	0.111	–	0.056	1.000	0.017	0.500	0.111	0.012	0.109	0.500	0.755
Tamil Nadu	–	0.533	1.000	0.800	–	0.133	1.000	0.648	0.800	0.800	0.886	0.886	0.800	0.413

U-values and the lower diagonal numbers indicate the corresponding *p*-values (exact significance [2×one-tailed significance])]

Satna Dt.	Narmada west	Narmada east	Jharkhand 1	Jharkhand 2	Maharashtra	Orissa 1	Orissa 2	Orissa 3	Andhra 1	Andhra 2	Andhra 3	Andhra 4	Karnataka	Tamil Nadu
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
0.000	4.000	4.000	0.000	2.500	2.000	0.000	0.000	2.000	0.000	0.000	0.000	2.000	6.500	2.000
0.000	2.000	1.000	1.000	1.000	1.000	1.000	1.000	4.000	0.000	1.000	1.000	0.000	0.000	2.000
0.000	5.500	3.000	1.000	2.000	3.000	4.000	2.000	6.000	0.000	1.000	1.000	1.000	1.000	3.000
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
0.000	0.500	0.500	0.000	1.500	2.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.000	0.000
0.000	8.500	4.000	1.000	4.500	4.000	4.000	2.000	8.000	2.000	4.000	2.000	2.000	10.000	6.000
0.000	17.500	8.500	4.000	7.500	10.000	11.000	6.500	24.500	5.000	9.000	6.000	3.000	6.500	11.000
0.000	2.000	0.000	0.000	1.000	1.000	0.500	0.500	2.000	0.000	0.000	0.000	1.000	1.500	1.000
0.000	5.500	2.500	1.000	2.000	3.000	3.500	2.000	7.000	1.500	2.500	2.000	1.000	1.500	3.000
0.000	8.500	4.000	3.000	4.000	4.000	5.000	3.000	15.500	2.500	6.500	3.000	1.000	1.000	7.000
2.500	9.500	4.000	3.000	4.000	5.000	8.000	4.000	15.500	4.000	7.500	4.000	2.000	5.500	7.000
0.000	1.500	2.000	0.000	2.000	1.000	0.000	0.000	1.000	0.000	0.000	0.000	1.000	1.500	1.000
0.000	11.000	10.000	1.000	9.500	6.500	13.000	2.500	8.500	1.500	3.000	2.000	4.000	15.000	6.000
–	2.500	0.000	2.000	5.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
0.009	–	10.000	3.000	9.500	8.000	12.000	5.500	18.000	3.500	7.500	4.000	4.500	14.500	10.000
0.010	0.762	–	2.000	8.000	6.000	7.000	2.500	9.500	1.500	3.500	3.000	2.500	13.500	5.000
0.286	0.429	0.533	–	2.000	1.000	1.000	1.000	5.000	2.000	3.000	2.000	0.500	0.500	2.000
0.082	0.329	0.730	0.381	–	7.000	4.000	2.000	9.500	2.000	4.000	2.000	4.500	10.000	6.000
0.024	0.905	1.000	0.400	1.000	–	6.000	3.000	8.000	2.000	4.500	2.000	3.000	8.000	5.500
0.010	1.000	0.886	0.267	0.190	1.000	–	3.500	11.000	1.000	3.000	2.000	3.000	3.500	6.000
0.071	0.857	0.533	0.667	0.381	1.000	0.800	–	7.000	1.500	2.500	2.000	1.000	1.500	3.000
0.001	0.491	0.283	0.533	0.127	0.497	0.461	0.889	–	6.500	14.500	8.000	3.000	10.000	14.000
0.071	0.429	0.267	1.000	0.381	0.800	0.267	0.667	0.711	–	4.000	0.000	0.000	0.000	4.000
0.010	0.352	0.200	0.800	0.190	0.629	0.200	0.533	0.808	1.000	–	2.000	1.000	1.000	7.500
0.071	0.643	0.800	1.000	0.381	0.800	0.533	1.000	1.000	0.333	0.533	–	0.000	0.000	4.000
0.071	0.643	0.533	0.333	0.857	1.000	0.800	0.667	0.267	0.333	0.267	0.333	–	6.500	2.000
0.001	0.366	0.927	0.056	0.268	0.667	0.042	0.111	0.040	0.056	0.012	0.056	0.889	–	8.000
0.010	0.762	0.486	0.533	0.413	0.857	0.686	0.800	0.808	1.000	0.886	1.000	0.533	0.315	–

Table 6.6 Inter-group *Mann–Whitney U*-test results for the refinement variable [upper diagonal numbers indicate Mann–Whitney

	Milestone 101	Satpati and Bhimbandh	Hoshiarpur area	Delhi area	Belan Valley	U.P. area	W. Rajasthan	Berach Valley	Didwana region	E. Rajasthan	C. Rajasthan	Gujarat	E. Malwa	Son Valley
Milestone 101	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Satpati and Bhimbandh	–	–	1.000	1.000	–	1.000	3.000	2.000	5.000	2.000	2.000	1.000	1.000	3.000
Hoshiarpur area	–	1.000	–	0.000	–	0.500	1.000	1.000	2.500	1.000	0.000	0.500	0.000	2.000
Delhi area	–	0.667	0.667	–	–	0.000	1.500	0.000	0.000	2.000	0.000	0.000	0.000	1.500
Belan Valley	–	–	–	–	–	–	–	–	–	–	–	–	–	–
U.P. area	–	0.667	0.667	0.333	–	–	1.000	6.000	8.500	1.000	4.000	3.500	2.000	3.000
W. Rajasthan	–	1.000	1.000	0.400	–	0.400	–	2.000	5.000	3.000	2.000	1.000	1.000	4.000
Berach Valley	–	0.222	0.500	0.056	–	0.889	0.067	–	22.500	2.500	9.500	10.500	5.500	14.500
Didwana region	–	0.308	0.500	0.026	–	0.641	0.088	0.151	–	9.000	20.000	10.000	9.500	23.000
E. Rajasthan	–	1.000	1.000	1.000	–	0.667	1.000	0.222	0.769	–	3.000	1.000	1.000	2.500
C. Rajasthan	–	0.533	0.400	0.133	–	1.000	0.229	0.412	0.851	0.800	–	4.000	3.500	9.000
Gujarat	–	0.267	0.400	0.133	–	0.800	0.114	0.527	0.138	0.267	0.343	–	2.000	7.000
E. Malwa	–	0.667	0.667	0.333	–	1.000	0.400	0.667	0.769	0.667	0.800	0.533	–	5.000
Son Valley	–	0.571	1.000	0.190	–	0.571	0.393	0.639	0.661	0.381	0.905	0.556	1.000	–
Satna Dt.	–	0.143	0.286	0.071	–	1.000	0.048	1.000	0.216	0.286	0.171	0.352	0.429	0.931
Narmada west	–	0.143	0.571	0.143	–	1.000	0.095	0.234	0.048	0.143	0.171	0.476	0.429	0.177
Narmada east	–	0.133	0.400	0.133	–	0.800	0.057	0.412	0.026	0.267	0.114	0.886	0.267	0.286
Jharkhand 1	–	1.000	1.000	0.333	–	0.667	0.800	0.222	0.308	1.000	0.133	0.267	0.333	0.857
Jharkhand 2	–	0.571	0.333	1.000	–	0.095	0.571	0.005	0.005	0.571	0.016	0.016	0.095	0.095
Maharashtra	–	0.533	0.800	0.533	–	0.800	0.400	0.927	0.280	0.267	0.486	0.686	0.800	0.905
Orissa 1	–	0.133	0.400	0.133	–	1.000	0.057	0.648	0.104	0.533	0.343	0.486	0.800	0.905
Orissa 2	–	0.333	0.667	0.333	–	1.000	0.200	1.000	0.410	0.667	0.533	0.800	0.667	0.857
Orissa 3	–	0.267	0.667	0.044	–	0.533	0.085	0.955	0.545	0.400	0.933	0.808	1.000	0.833
Andhra 1	–	0.800	1.000	0.267	–	0.533	0.629	0.073	0.661	0.800	0.486	0.114	0.533	0.413
Andhra 2	–	0.533	0.400	0.800	–	0.133	0.629	0.012	0.018	1.000	0.029	0.029	0.133	0.190
Andhra 3	–	0.667	1.000	0.333	–	0.667	0.400	0.667	0.769	0.667	1.000	0.533	1.000	0.857
Andhra 4	–	0.333	0.667	0.333	–	0.333	0.200	0.056	0.026	0.333	0.133	0.133	0.333	0.095
Karnataka	–	0.056	0.250	0.056	–	1.000	0.017	0.128	0.000	0.111	0.012	0.527	0.111	0.202
Tamil Nadu	–	0.133	0.400	0.133	–	0.800	0.057	0.788	0.104	0.533	0.200	1.000	0.533	0.556

U-values and the lower diagonal numbers indicate the corresponding *p*-values (exact significance [2×one-tailed significance])]

Satna Dt.	Narmada west	Narmada east	Jharkhand 1	Jharkhand 2	Maharashtra	Orissa 1	Orissa 2	Orissa 3	Andhra 1	Andhra 2	Andhra 3	Andhra 4	Karnataka	Tamil Nadu
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1.500	1.500	0.000	2.000	3.000	2.000	0.000	0.500	3.500	3.000	2.000	1.000	0.000	0.000	0.500
0.000	1.000	0.000	1.000	0.500	1.000	0.000	0.000	2.500	2.000	0.500	1.000	0.000	0.000	0.000
0.000	1.000	0.000	0.000	5.000	2.000	0.000	0.000	0.000	1.500	3.000	0.000	0.000	0.000	0.000
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
6.000	6.000	3.000	1.000	0.500	3.000	4.000	2.000	5.500	2.000	0.500	1.000	0.000	7.000	3.000
1.500	2.500	0.000	2.000	5.000	3.000	0.000	0.500	3.500	4.000	4.000	1.000	0.000	0.000	0.500
21.000	12.000	9.000	2.000	1.000	13.000	11.500	7.000	27.000	4.500	1.000	5.000	0.000	12.000	12.000
20.000	13.000	5.000	5.000	4.000	13.000	9.500	6.500	36.000	18.500	4.000	9.000	0.000	3.500	9.500
2.000	1.000	1.000	2.000	3.000	1.000	2.500	1.000	4.000	3.500	4.000	1.000	0.000	1.000	2.000
5.500	5.000	2.000	0.000	0.000	5.000	4.500	2.000	15.000	5.500	0.000	4.000	0.000	1.500	3.500
7.500	8.000	7.000	1.000	0.500	6.500	5.000	3.000	14.500	2.000	0.500	2.000	0.000	10.500	8.000
3.000	3.000	1.000	0.000	0.000	3.000	3.000	1.000	8.000	2.000	0.000	2.000	0.000	1.000	2.000
14.000	7.000	5.500	4.000	4.500	9.000	9.500	4.500	18.000	6.500	4.500	4.000	0.000	9.500	7.500
–	10.000	4.000	0.000	0.000	10.000	12.000	4.500	21.500	4.000	0.000	6.000	0.000	4.000	8.500
0.240	–	11.000	2.000	3.000	6.000	5.000	3.000	14.000	3.000	2.000	3.000	0.000	15.500	10.000
0.114	0.914	–	0.000	0.000	7.000	4.500	1.500	10.000	2.000	0.000	2.000	1.500	12.500	6.500
0.071	0.286	0.133	–	1.000	2.000	0.000	0.000	5.000	4.000	1.000	2.000	0.000	0.000	0.000
0.004	0.030	0.016	0.190	–	3.000	0.000	0.000	3.500	4.500	8.000	1.000	0.000	0.000	0.000
0.762	0.257	0.886	0.533	0.111	–	5.000	3.000	14.000	4.000	4.000	3.000	0.000	10.000	8.000
1.000	0.171	0.343	0.133	0.016	0.486	–	3.000	15.000	4.000	0.000	4.000	0.000	4.000	7.500
0.643	0.429	0.267	0.333	0.095	0.800	0.800	–	7.500	2.000	0.000	2.000	0.000	1.500	3.000
0.755	0.228	0.368	0.533	0.011	0.808	0.933	0.889	–	9.000	3.500	7.000	0.000	20.500	11.500
0.114	0.067	0.114	1.000	0.190	0.343	0.343	0.533	0.283	–	4.500	2.000	0.000	1.500	3.500
0.010	0.038	0.029	0.267	0.730	0.343	0.029	0.133	0.028	0.343	–	1.000	0.000	0.000	0.000
1.000	0.429	0.533	1.000	0.190	0.800	1.000	1.000	0.889	0.533	0.267	–	0.000	3.000	3.000
0.071	0.071	0.267	0.333	0.095	0.133	0.133	0.333	0.044	0.133	0.133	0.333	–	0.000	2.000
0.014	0.445	0.788	0.056	0.003	0.527	0.073	0.111	0.397	0.012	0.006	0.333	0.056	–	9.000
0.476	0.762	0.686	0.133	0.016	1.000	0.886	0.800	0.461	0.200	0.029	0.800	0.533	0.412	–

is that many surface sites, from where most of these assemblages in the study sample derive, yield a mixture of Early and Late Acheulean handaxes. This may be true if the same geographic source(s) of raw material was exploited repeatedly over hundreds of thousands of years. When considering the differences between these assemblages based on the five concerned variables, handaxe groups appeared to exhibit higher frequencies of statistical differences from each other in their thickness, followed by their length, refinement and breadth. Comparatively, they were not as statistically different from each other in their elongation values as they were in other variables.

Summary and Conclusions

The metric compilation of published South Asian handaxe assemblages illustrates a greater range of metric variability than previously acknowledged. When these handaxes assemblages were sorted according to their respective variables, several important observations were made. Given the full range of dimensions and related attributes, all South Asian Acheulean handaxe assemblages cannot be strictly divided into Early and Late phases. Indeed, as more absolute dates and detailed metric data become available, current classifications of many Acheulean assemblages are likely to change. In other words, instead of two separate Mode 2 dispersals from Africa (e.g., Bar-Yosef and Belfer-Cohen 2001), there appears to have been an intermediate developmental stage within the Indian subcontinent and significantly marked by geographically overlapping metric variance.

With a few exceptions, most assemblages or spatially discrete localities are dimensionally "homogeneous" probably because they are found in a shared stratigraphic contexts and are thus contemporaneous and possibly made by the same populations. That being said, there is, in the broadest sense, some tentative geographic patterning with refinement and thus thickness. There is no clear geographic patterning with other variables; in other words, there is considerable overlap of attributes between geographic zones. Groups with the least metric variation against other groups dominate the northern and central regions respectively, and only about six groups are statistically the most different from other groups and again, no geographic patterning is clearly visible. At times, there is greater similarity between two groups farther apart geographically than between two groups geographically close to each other. Therefore, in terms of addressing Question 3 – that groups of assemblages closest to each other are the most similar – the answer is definitely, no. Likewise in the cluster analyses, most handaxe assemblages that come from the same area and thus are presumably technomorphologically similar and broadly contemporaneous (e.g., Sharda Temple localities I to IV) did not consistently group together but instead ranked separately on the three resulting dendrograms. In other words, there was no consistent placement of assemblages based on their respective metric variables. In addition, the three dendrograms generated demonstrate that specific assemblages

which are presumably thought to be either Early or Late Acheulean, often cluster together in the same "branch." This further reinforces that the five variables used are not always adequate to techno-chronologically distinguish or broadly categorize handaxe assemblages as has been previously done by some researchers. Additional metric and technological attributes and related details need to be quantified and taken into account, especially when absolute dates are not available. The preliminary results of the cluster analyses also suggest that there must have been an intermediate Acheulean developmental phase between the earliest and youngest handaxe industries. Although absolute dates are currently lacking for most known assemblages, the temporal span of this intermediate phase may be in excess of a half million years, ample time for the South Asian Acheulean to attain regional character(s) and variable morphological properties. Although this inference requires confirmation, the large amount of inter-assemblage metric variation seen in South Asian handaxe assemblages may be due in part to their maximum distance from East Africa, the geographic source of Acheulean technological origins (see Lycett and von Cramon-Taubadel 2008). Only long-term multidisciplinary investigations in different ecozones of South Asia will reveal whether the levels of statistical differences in handaxe metric variation are truly related to hominin behavioral patterns (e.g., typocultural dynamics within the Mode 2 system, biface function, multiple and intensive dispersals within the subcontinent over time) and/or whether other independent factors have also come into play (e.g., geographic constraints in raw material quality and size, respective ages of the individual assemblages).

It is important to note that the results and interpretations in this pilot study are preliminary and additional detailed comparisons and observations are currently in progress. Future goals for this ongoing study will also include factoring in specific ecogeographic and geostratigraphic contexts and typological frequencies to examine which types of handaxes are found in which contexts and a similar study as presented here is also in progress for South Asian Acheulean cleavers, for which comparable metric data is also available in the published literature. In order to shed further light on such key concepts as Mode 2 dispersals, ecological adaptations, regional diversity, land-use patterns, technological variation, and so forth, the Indian subcontinent provides an ample and promising source of Acheulean data. Such basic methods as demonstrated in this paper can also easily be applied at a global level to reveal interesting geographic patterns of metrical similarities and differences across the Acheulean domain, particularly in relation to such associated factors as raw material types, handaxe shapes, paleoenvironmental contexts, and discrete ecological preferences.

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References

Ahmad., K. 1978–79. Prehistory of Dadra and Nagar Haveli. *Puratattva* 10: 87–89.

Allchin, B., Goudie, A. and Hegde, K., 1978. *The Prehistory and Palaeogeography of the Great Indian Desert*. Academic, New York.

Ansari, Z.D. and Pappu, R.S., 1973. Stone Age in Kutch, Gujarat. *Bulletin of the Deccan College Postgraduate and Research Institute* 32: 150–167.

Ashraf, A.A., 1990. *Prehistoric Archaeology of Lower Subansiri – An exploratory report on the investigations into the prehistoric archaeology in and around itanagar, Lower Subansiri District of Arunachal Pradesh*. Directorate of Research, Government of Arunachal Pradesh, Itanagar.

Bar-Yosef, O. and Belfer-Cohen, A., 2001. From Africa to Eurasia – early dispersals. *Quaternary International* 75: 19–28.

Bednarik, R.G., Kumar, G., Watchman, A. and Roberts, R.G., 2005. Preliminary results of the EIP Project. *Rock Art Research* 22: 147–197.

Behera, P.K., Panda, P. and Thakur, N., 1996. Techno-typological analysis of lithic artefacts from the Dari-dungri Acheulian Site, Sambalpur District, Orissa. *Man and Environment* 21: 15–26.

Biagi, P., Kazi, M.M. and Negrino, F., 1996. An Acheulian Workshop at Ziarat Pir Shaban on the Rohri Hills, Sindh Pakistan. *South Asian Studies* 12: 49–62.

Bhaskar, S., 1990. *Prehistoric and Primitive Hunter-Gatherers of South India*. Discovery Publishing House, New Delhi.

Blackwell, B.A.B., Montoya, A., Blickstein, J.I.B., Skinner, A.R., Pappu, S., Gunnell, Y., Taieb, T., Kumar, A. and Lundbergfet, J.A., 2007. ESR analyses for teeth from the open-air site at Attirampakkam, India: Clues to complex U uptake and paleoenvironmental change. *Radiation Measurements* 42: 1243–1249.

Blumenschine, R.J., Brandt, S.A. and Clark, J.D., 1983. Excavations and analysis of Middle Palaeolithic Artifacts from Patpara, Madhya Pradesh. In *Palaeoenvironments and Prehistory in the Middle Son Valley* (Madhya Pradesh, North-Central India), edited by G.R. Sharma and J.D. Clark, pp. 39–100. Abhinash Prakashan, Allahabad.

Bopardikar, B.P., 1985. Early Stone Age site at Manegaon on the Purna River, Jalgaon District, Maharashtra State. In *Studies in Indian Archaeology: Professor H.D. Sankalia Felicitation Volume*, edited by S.B. Deo and M.K. Dhavlaikar, pp. 8–12. Popular Prakashan, Bombay.

Bordes, F., 1961. *Typologie du Paléolithique ancien et moyen*. Institut de Préhistoire Université de Bordeaux, Bordeaux.

Bose, N. and Sen, D., 1948. *Excavations in Mayurbhanj*. University of Calcutta, Calcutta.

Bose, N.K., Gupta, P. and Bose, A., 1960. Palaeoliths from Monghyr District, Bihar. *Man in India* 40: 68–75.

Chakrabarti, D.K., 1993. *Archaeology of Eastern India: Chhotanagpur Plateau and West Bengal*. Munshiram Manoharlal Publishers Pvt. Ltd., New Delhi.

Chakrabarti, D.K. and Chattopadhyay, R.K., 1988. A note on the lithic industries of Mayurbhanj and Keonjhar, Orissa. *Man and Environment* 12: 197–201.

Chakrabarti, D.K. and Lahiri, N., 1987. A preliminary report on the Stone Age of the Union Territory of Delhi and Haryana. *Man and Environment* 11: 109–116.

Chakrabarti, S., 1983. Acheulian Culture in Saurashtra in Relation to Pleistocene Stratigraphy-An Overview. *Journal of Indian Anthropological Science* 18: 1–9.

Chauhan, P.R., 2004. A review of the Early Acheulian evidence from South Asia, *Assemblage* 8. http://www.shef.ac.uk/assem/issue8/chauhan.html; http://www.shef.ac.uk/assem/issue7/chauhan.html.

Chauhan, P.R., 2008. Large mammal fossil occurrences and associated archaeological evidence in Pleistocene contexts of peninsular India and Sri Lanka. *Quaternary International* 192: 21–42.

Chauhan, P.R., 2009. The Lower Paleolithic of the Indian Subcontinent. *Evolutionary Anthropology* 18: 62–78.

Chauhan, P.R., 2010. Core-and-flake assemblages of India. In *Asian Paleoanthropology: From Africa to China and Beyond*, edited by C.J. Norton and D. Braun. Kluwer-Academic Press, New York (in press).

Chauhan, P.R. and Patnaik, R., 2008. Pilikarar – An Early Acheulean site in the central Narmada Basin (central India). Manuscript in possession of the authors.

Corvinus, G., 2006. Acheulian handaxes from the Upper Siwalik in Nepal. In *Axe Age: Acheulian Tool-Making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 415–428. Equinox, London.

Crompton, R.H. and Gowlett, J.A.J., 1993. Allometry and multidimensional form in Acheulean bifaces from Kilombe, Kenya. *Journal of Human Evolution* 25: 175–199.

Deo, S.G., Mishra S., Rajaguru S.N. and Ghate S., 2007. Antiquity of Acheulian culture in upland Maharasthra: a geoarchaeological approach. In *Genome and People of India*, edited by A.R. Sankhyan, pp. 292–308. Concept Publishers, Calcutta.

Deotare, B.C., Kajale, M.D., Rajaguru, S.N., Kusumgar, S., Jull, A.J.T. and Donahue, J.D., 2004. Paleoenvironmental History of the Bap-Malar and Kanod playas of western Rajasthan, Thar Desert. *Proceedings of the Indian Academy of Sciences (Earth Planetary Sciences)* 113: 403–425.

Dytham, C., 2003. *Choosing and Using Statistics – A Biologist's Guide*. 2nd Edition. Blackwell, Oxford.

Gaillard, C. and Murty, M.L.K., 1988. Typo-technological comparison of two Acheulian assemblages at Renigunta, South India. *Man and Environment* 12: 123–133.

Gaillard, C., Misra, V.N. and Murty, M.L.K., 1990. Comparative study of three series of handaxes: one from Rajasthan and two from Andhra Pradesh. *Bulletin of the Deccan College Postgraduate and Research Institute* 49: 137–143.

Gaillard, C., Raju, D.R., Misra, V.N. and Rajaguru, S.N., 1986. Handaxe assemblages from the Didwana region, Thar Desert, India: a metrical analysis. *Proceedings of the Prehistoric Society* 52: 189–214.

Ghosh, AK., 1985. An attempt to understand the Acheulian succession in India from spatial distributions. In *Recent Advances in Indo-Pacific Prehistory*, edited by V.N. Misra and P. Bellwood, pp. 29–34. Oxford and IBH, New Delhi.

Goren-Inbar, N. and Sharon, G., 2006. *Axe Age – Acheulian Tool-making from Quarry to Discard*. Equinox, London.

Gowlett, J.A.J., 1996. Mental abilities of early Homo: elements of constraint and choice in rule systems. In *Modelling the Early Human Mind*, edited by P. Mellars and K. Gibson, pp.191–215. McDonald Institute, Cambridge.

Hou, Y.M., Potts, R., Yuan, B., Guo, Y., Deino, Z.T., Wang, A., Clark, W., Xie, J. and Huang, W.W., 2000. Mid-Pleistocene Acheulean-like stone technology of the Bose Basin, South China. *Science* 287: 1622–1626.

Jacobson, J., 1975. Early Stone Age habitation in eastern Malwa. *Proceedings of the American Philosophical Society* 119: 280–297.

Jayaswal, V., 1982. *Chopper-Chopping Component of Palaeolithic India*. Agam Kala Prakashan, New Delhi.

Jayaswal, V., 1978. *Palaeohistory of India: A Study of the Prepared Core Technique*. Agam Kala Prakashan, New Delhi.

Joshi, R.V., 1955. *Pleistocene Studies in the Malaprabha Basin*. The Deccan College Research Institute and the Karnataka University Publication No. 1. Karnataka University, Dharwar.

Joshi, R.V. and Marathe, A.R., 1975–1976. Metrical analysis of handaxes from Chirki-on-Pravara (Western Maharashtra, India). *Puratattva* 8: 3–12.

Kenoyer, J.M. and Pal, J.N., 1983. Report on the excavation and analysis of an Upper Acheulian assemblage from Sihawal II. In *Palaeoenvironments and Prehistory in the Middle Son Valley* (Madhya Pradesh, North-Central India), edited by G.R. Sharma and J.D. Clark, pp. 23–38. Abhinash Prakashan, Allahabad.

Khatri, A.P., 1958. Stone Age tools of the Gambhiri Basin (south-eastern Rajasthan). *Journal of the University of Bombay* 26: 35–49.

Khatri, A.P., 1962. 'Mahadevian': an Oldowan pebble culture of India. *Asian Perspectives* 6: 186–197.

Khatri, A.P., 1963. Prehistoric cultures of Malwa (Central India). *Anthropos* 58: 485–506.

Khatri, A.P., 1964. Recent exploration for the remains of early man in India. *Asian Perspectives* 7: 160–182.

Korisettar, R., 2002. The archaeology of the south Asian Lower Palaeolithic: history and current status. In *Indian Archeology in Retrospect: Archaeology and Interactive Disciplines*, edited by S. Settar and R. Korisettar, pp. 1–65. Manohar and Indian Council of Historical Research, New Delhi.

Krishnaswami, V.D. and Soundarajan, K.V., 1951. The lithic tool-industries of the Singrauli Basin. *Ancient India* 7: 40–65.

Kumar, A., 1989. A metrical analysis of handaxes and cleavers from the Acheulian site at Gangapur, Nasik District, Maharasthra. *Man and Environment* 13: 49–63.

Lal, M. and Salahuddin, 1989–1990. Deogarh Acheulian assemblage: a preliminary report. *Puratattva* 20: 65–70.

Lycett, S.J. and von Cramon-Taubadel, N., 2008. Acheulean variability and hominin dispersals: a model-bound approach. *Journal of Archaeological Science* 35: 553–562.

Lycett, S.J. and Gowlett, J.A.J., 2008. On questions surrounding the Acheulean 'tradition'. *World Archaeology* 40: 295–315.

Machin, A.J., Hosfield, R.T. and Mithen, S.J., 2007. Why are some handaxes symmetrical? Testing the influence of handaxe morphology on butchery effectiveness. *Journal of Archaeological Science* 34: 883–893.

Marathe, A., 1981. *Geoarchaeology of the Hiran Valley, Saurashtra India*. Deccan College Postgraduate and Research Institute, Poona.

McPherron, S.P., 1994. *A Reduction Model for Variability in Acheulean Biface Morphology*. Unpublished PhD Dissertation. University of Pennsylvania, Philadelphia.

McPherron, S.P., 2000. Handaxes as a measure of the mental capabilities of early hominids. *Journal of Archaeological Science* 27: 655–663.

Mishra, S., 1982. On the effects of basalt weathering on the distribution of Lower Paleolithic sites in the Deccan. *Bulletin of the Deccan College Postgraduate and Research Institute* 41: 107–115.

Mishra, S., 1995. Chronology of the Indian Stone Age: the impact of recent absolute and relative dating attempts. *Man and Environment* 20: 11–16.

Mishra, S., 2006–2007. The Indian Lower Palaeolithic. *Bulletin of the Deccan College Postgraduate and Research Institute* 66–67: 47–94.

Mishra, S., Venkatesan, T.R. and Somayajulu, B.L.K., 1995. Earliest Acheulian industry from peninsular India. *Current Anthropology* 36: 847–851.

Misra, V.D., 1977. *Some Aspects of Indian Archaeology*. Prabhat Prakashan, Allahabad.

Misra, V.D., 1997. Lower and Middle Palaeolithic cultures of Northern Vindhyas. In, *Indian Prehistory: 1980*, edited by V.D. Misra and J.N. Pal, pp. 61–74. Department of Ancient History, Culture and Archaeology, University of Allahabad, Allahabad.

Misra, V.D., Rana, R.S., Clark, J.D. and Blumenschine, R.J., 1983. Preliminary Excavations at the Son River Section at Nakjhar Khurd. In *Palaeoenvironments and Prehistory in the Middle Son Valley* (Madhya Pradesh, North-Central India), edited by G.R. Sharma and J.D. Clark, pp. 101–115. Abhinash Prakashan, Allahabad.

Misra, V.N., 1962. Palaeolithic industry of the Banas, eastern Rajputana. *Journal of the Asiatic Society of Bombay* 34–35: 138–160.

Misra, V.N., 1963. Palaeolithic culture of Western Rajputana. *Bulletin of the Deccan College Research Institute* 21: 85–156.

Misra, V.N., 1967. *Pre- and Proto-history of the Berach Basin (South Rajasthan)*. Deccan College Postgraduate and Research Institute, Poona.

Misra, V.N., 1987. Middle Pleistocene adaptations in India. In *The Pleistocene Old World: Regional Perspectives*, edited by O. Soffer, pp. 99–119. Plenum Press, New York.

Misra, V.N., 1989. Stone Age India: an ecological perspective. *Man and Environment* 14: 17–64.

Misra, V.N. and Nagar, M., 1961–1962. Two Stone Age sites on the River Chambal, Rajasthan. *Bulletin of the Deccan College Research Institute* 22: 156–169.

Mohanty, P., Basa, K.K. and Tripathy, B., 1997. Stone Age cultures of Mayurbhanj District, Orissa. *Man in India* 77: 159–177.

Mohapatra, G.C., 1962. *The Stone Age Cultures of Orissa*. Deccan College Postgraduate and Research Institute, Pune.

Mohapatra, G.C., 1981. Acheulian discoveries in the Siwalik frontal range. *Current Anthropology* 22: 433–435.

Mohapatra, G.C., 1982. Acheulian discoveries in the Siwaliks of Punjab. In *Indian Archaeology: New Perspectives* edited by R.K. Sharma, pp. 28–37. Agam Kala Prakashan, Delhi.

Noll, M. and Petraglia, M.D., 2003. Acheulean bifaces and early human behavioral patterns in East Africa and South India. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H. Dibble, pp. 31–53. University of Pennsylvania Press, Philadelphia.

Norton, C.J., Bae, K., Harris, J.W.K. and Lee, H., 2006. Middle Pleistocene handaxes from the Korean Peninsula. *Journal of Human Evolution* 51: 527–536.

Paddayya, K., 1977. The Acheulian Culture of the Hunsgi Valley (Shorapur Doab), Peninsular India. *Proceedings of the American Philosophical Society* 121: 383–406.

Paddayya K., 1984. Stone Age India. In *Neue Forschungen zur Altsteinseit*, edited by H. Muller-karp. C.H. Beck Verlag, Munich.

Paddayya, K., Blackwell, B.A.B., Jhaldiyal, R., Petraglia, M.D., Fevrier, S., Chaderton II, D.A., Blickstein, J.I.B. and Skinner, A.R., 2002. Recent findings on the Acheulian of the Hunsgi and Baichbal valleys, Karnataka, with special reference to the Isampur excavation and its dating. *Current Science* India 83: 641–647.

Pappu, R.S., 2001a. *Acheulian Culture in Peninsular India*. D.K. Printworld, New Delhi.

Pappu, S., 2001b. *A Re-examination of the Palaeolithic Archaeological Record of Northern Tamil Nadu, South India*. BAR International Series 1003, Oxford.

Pappu, R.S., 1970–1971. Explorations of prehistoric sites in District Bijapur. *Puratattva* 4: 58–62.

Pappu, R.S., 1974. *Pleistocene Studies in the Upper Krishna Basin*. Deccan College Postgraduate and Research Institute, Poona.

Pappu, S. and Akilesh, K., 2006. Preliminary observations on the Acheulian assemblages from Attirampakkam, Tamil Nadu. In *Axe Age: Acheulian Tool-Making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 155–180. Equinox, London.

Pappu, S., Gunnell, Y., Taieb, M., Brugal, J.P. and Touchard, Y., 2003. Excavations at the Palaeolithic site of Attirampakkam, South India: preliminary findings. *Current Anthropology* 44: 591–597.

Patnaik, R., Chauhan, P.R., Rao, M.R., Blackwell, B.A.B., Skinner, A.R., Sahni, A., Chauhan, M.S. and Khanm H.S., 2009. New geochronological, palaeoclimatological and archaeological data from the Narmada Valley hominin locality, central India. *Journal of Human Evolution* 56: 114–133.

Petraglia, M.D., 1998. The Lower Palaeolithic of India and its bearing on the Asian record. In *Early Human Behavior in Global Context: The Rise and Diversity of the Lower Palaeolithic Record*, edited by M.D. Petraglia and R. Korisettar, pp. 343–90. Routledge, New York.

Petraglia, M.D., 2006. The Indian Acheulean in global perspective. In *Axe Age: Acheulean Tool-making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 389–414. Equinox, London.

Raju, D.R., 1985. Handaxe assemblages from the Gunjana Valley, Andhra Pradesh: a metrical analysis. *Bulletin of the Indo-Pacific Prehistory Association* 1985: 10–26.
Raju, D.R., 1988. *Stone Age Hunter-Gatherers: An Ethno-Archaeology of Cuddapah Region, South-East India*. Ravi Publishers, Pune.
Rao, V.V.M., 1979. Discovery of Stone Age sites in the Paleru Valley-Coastal Andhra Pradesh. *Current Science* 48: 349–350.
Rao, V.V.M., 1983. Metrical analysis of Acheulian tools from the Paleru Valley, Coastal Andhra. In *Rangavalli: Recent Research in Indology (S.R. Rao Felicitation)*, edited by A.V. Narasimha Murthy and G. Rao, pp. 11–17. Sundeep Prakashan, Delhi.
Reddy, V.R. and Bhaskar, S., 1983. Maralipalem and Chintalapalem: two Late Acheulian sites in southeast Andhra Pradesh. In *Rangavalli: Recent Research in Indology (S.R. Rao Felicitation)*, edited by A.V. Narasimha Murthy and G. Rao, pp. 19–43. Sundeep Prakashan, Delhi.
Rishi, K.K., 1989. *Palaeoliths from Atbarapur (Punjab)*. Department of Cultural Affairs Archaeology and Museums, Punjab.
Roe, D., 1964. The British Lower and Middle Palaeolithic: some problems, methods of study and preliminary results. *Proceedings of the Prehistoric Society* 34: 245–267.
Roe, D.A., 1968. British Lower and Middle Palaeolithic handaxe groups. *Proceedings of the Prehistoric Society* 34: 1–82.
Sankalia, H.D., 1974. *The Prehistory and Protohistory of India and Pakistan*. Deccan College and Postgraduate Research Institute, Pune.
Sankalia, H.D., 1976. The Early and Middle Palaeolithic Cultures in India and Pakistan. In *Le Paeolithique Inferieu et Moyen en Indie, en Asie Centrale, en Chine et dans le sud-est Asiatique*. Colloque VII UISPP (Nice): 7–30.
Santonja, M. and Villa, P., 2006. The Acheulian of western Europe. In *Axe Age – Acheulian Tool-making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 429–478. Equinox, London
Saragusti, I. and Goren-Inbar, N., 2001. The bifaces assemblage from Gesher Benot Ya'aqov, Israel: illuminating patterns in "Out of Africa" dispersal. *Quaternary International* 75: 85–89.
Semans, C., 1981. Analysis of an Acheulian collection from Peera Nullah, Narmada Valley, India. *Man and Environment* 5: 13–31.
Sharma, A.K., 1993. *Prehistoric Delhi and Its Neighborhood*. Aryan Books International, New Delhi.
Sharma, D.P. and Sharma, M., 2005. Pleistocene stratigraphy of Middle Narmada Valley. In *Palaeolithic Age – Pre-historic Art and Archaeology of South Asia (Vol. 1)*, edited by D.P. Sharma, S.K. Singh and M. Sharma, pp. 83–109. Bharatiya Kala Prakashan, New Delhi.
Sharma, D.P., Singh, S.K. and Sharma, M., 2004. *Pre-Historic Art and Archaeology of South Asia: Palaeolithic Age*. Volumes 1 and 2. Baratiya Kala Prakashan, New Delhi.
Singh, O.K. and Singh, R.K.R., 1990. A preliminary report on an archaeological exploration at Singtom, Chandel District, Manipur. *Man and Environment* 15: 103–106.
Sinha, P., 1991. *Model for Land-Use in Late Acheulian Tradition (Satna District, M.P.)*. Prayag Pustak Sadan, Allahabad.
Soressi, M. and Dibble, H.L. (eds.), 2003. *Multiple Approaches to the Study of Bifacial Technologies*. University of Pennsylvania Museum Press, Philadelphia.
Supekar, S.N., 1968. *Pleistocene Stratigraphy and Prehistoric Archaeology of the Central Narmada Basin*. Unpublished Ph.D. Dissertation. University of Poona, Pune.
Szabo, B.J., McKinney, C., Dalbey, T.S. and Paddayya, K., 1990. On the age of the Acheulian culture of the Hunsgi-Baichbal Valleys, Peninsular India. *Bulletin of the Deccan College Postgraduate and Research Institute* 50: 317–321.
de la Torre, I., Mora, R. and Martinez-Moreno, J., 2008. The early Acheulean in Peninj (Lake Natron, Tanzania). *Journal of Anthropological Archaeology* 27: 244–264.
Wynn, T. and Tierson, F., 1990. Regional comparison of the shapes of later Acheulean handaxes. *American Anthropologist* 92: 73–84.

Chapter 7
Quantifying Variation in Landscape-Scale Behaviors: The Oldowan from Koobi Fora

David R. Braun, Michael J. Rogers, John W. Harris, and Steven J. Walker

Abstract Studies of stone artifact morphology are beginning to rapidly increase in complexity. While these techniques provide new insights into artifact variation, it is also necessary to insure that these methods provide data that is behaviorally relevant. Here, we provide a new technique that includes three dimensional attributes to calculate platform areas to enhance the prediction of flake area from platform attributes. This data allows the calculation of more precise measures of reduction in large unifacial flake cores in Developed Oldowan assemblages (i.e., Karari Scrapers). Here, we look at measures of curation within these tool types across a landscape scale study. We apply demographic analyses of the degree to which an assemblage can be considered to be curated (i.e., the potential use life of a tool minus the actual use life of a tool). Results suggest that even though there is significant variation within a given paleogeographic setting, a higher frequency of pieces are used to their full potential in areas where raw material is predicted to have been scarce. These data suggest that hominins fulfill some aspects of a neutral model of artifact transport, yet likely make directed movements to transport tools to specific places on the ancient landscape.

Introduction

A major hurdle for archaeologists who study stone artifacts is bridging the gap between the variation in artifacts that is quantifiable and the variation in artifacts that is behaviorally meaningful. Although lithic analysts in the last few years have expanded the range of possible ways to investigate stone artifacts (Andrefsky 2005; Clarkson et al. 2006; Lycett et al. 2006) the real challenge is to link this variation with behavioral attributes. This challenge will require archaeologists to break out of previous molds that restrict lithic analysis to those attributes that can be measured

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using traditional techniques. As Dibble (1998) noted in his response to Davis and Shea's (1998) test of the unifacial scraper model, the real challenge in developing new methods is not systematic error (e.g., the error associated with deriving a more accurate formula for calculating flake size from platform attributes in this particular case). A rather more serious problem is random error, which is introduced by the failure of our measurement systems to faithfully represent the morphology of artifacts. Current evaluations of artifact form are limited by the restrictions of most measurement techniques to measure attributes typically in two dimensions.

This book, and the associated symposium, demonstrates that archaeologists are beginning to test the boundaries of new methodologies for investigating artifact variation. New and exciting avenues of research includes the groundbreaking new work that links brain function to methods of artifact production (Stout and Chaminade 2007; Stout et al. 2000, 2008). The most recent impact of these studies suggests that changes in stone artifact production may actually parallel changes in brain development. Considering the recent finds of small-brained hominins in association with stone artifacts (Brumm et al. 2006), this type of research will have broad ranging implications. Additionally, the application of geometric morphometric techniques promises to expand archaeologists' abilities to quantify variation. Recent applications of this methodology suggest that the massive amount of variation we have documented in stone tool production through time may actually be distilled into vectors which define the directions of removals through the course of artifact production (Clarkson et al. 2006). While these approaches are still in their infancy, the possibilities are tremendous. These new approaches and the associated mathematical rigor has influenced physical anthropology (Richtsmeier et al. 2002) and now shows promise for further enhancing lithic analysis. Recent applications of this type of methodology suggest that even large-scale evolutionary trends may be tied to artifact variation (Lycett and von Cramon-Taubadel 2008). If the methodological advances associated with this technology keep pace with the ambitious applications of this technique, then lithic analysis may begin to link artifact morphological data to major evolutionary processes in the same way that morphological variation in hominin fossils has (yet with much better sample sizes).

Although these are exciting new developments, lithic analysts must continue to question and explore the weaknesses of these new techniques in much the same way that previous methodological advances were interrogated (e.g., microwear Newcomer et al. 1986, etc.).

A major question that still needs to be addressed is whether increasing the accuracy of artifact morphological quantification will actually increase the accuracy of quantifying behavior. Lithic analysts still desperately need expectations of behavior that can be tested with stone artifacts. The use of agent-based models is rapidly advancing the application of artifact variation to real behavioral questions (Brantingham 2003; Brantingham et al. 2006; Kantner 2008; Wilson 2007). Unfortunately, some of these models suggest that the "adaptations" we previously thought we were documenting could have easily been produced through random behaviors. While this is a troubling conclusion, it forces the lithic analyst to investigate artifact variation in new ways. Models based on behavioral expectations from optimality may be useful. Yet as

Binford (2001) has suggested the archaeological record may require models based on the peculiar aspects of archaeological data (e.g., palimpsests, time averaging, differential discard of certain tool types). In addition to these expectations of behavior, lithic analysis will require a host of new methodologies that are better adapted to answering behavioral questions.

One such model of hominin behavior associated with stone artifacts is the calculation of "curation" (Binford 1979). Although the term is borrowed from methods of museum collection and storage, it has since taken on its own archaeological meaning. Although rarely agreed upon (Binford 2001; Odell 1996; Shott 1996), the model, which includes (among other things) aspects of artifact selection, transport, and differential discard, is frequently invoked whenever archaeologists assume some measure of forethought associated with the maintenance of stone tool kits (de Heinzelin et al. 1999). Although Binford (1979) first described the concepts of these different models of hominin behavior, the most recent in depth investigation of these models stems from the ethnographic and archaeological investigations of Shott and colleagues (Shott 1996, 2002; Shott and Ballenger 2007; Shott and Sillitoe 2001, 2005; Shott and Weedman 2007). Shott's investigations continue to probe the interrelated nature of curative behaviors, artifact use-life, and the formation of the archaeological record. An oft-forgotten principle of the archaeological record is that those parts of the hominin tool kit that have the longest use-lives (and presumably therefore have the highest value to ancient toolmakers) will also enter the archaeological record very infrequently. Thus, representation in the material record may actually be negatively correlated with importance in the hominin tool kit. Imagine an excavation of a modern carpenter's tool kit. If we based importance on abundance, then nails would seem far more important than hammers.

Here, we describe a study of the landscape distribution of a single tool type (single-platform core or "Karari Scraper") in the Koobi Fora Formation of northern Kenya (Brown and Feibel 1986). We employ new techniques to measure aspects of artifact reduction that allows for a more accurate assessment of the degree of reduction. We use neutral models proposed by Brantingham (2003) to test the archaeological record against expected outcomes of a curated industry. In addition, we examine the distribution of these measures within specific groups to measure the nature of use-life amongst these particular tool types in tool kits of the earliest hominins.

Background

The Developed Oldowan industry was first described by Mary Leakey (1975) and was defined as a series of assemblages that include the archaic tool types of the Oldowan as well as the appearance of some forms that appear to have a higher degree of standardization (Ludwig 1999). Although the reality of this distinction has been the subject of some debate (Gowlett 1986), many archaeologists who study the Plio-Pleistocene would agree that by 1.5 Ma, the archaeological record appears to have changed (Kimura 2002; Rogers et al. 1994). This study will focus on the local expression of this industry in the Koobi Fora Formation (Feibel et al. 1989), which

has often been described as the “Karari Industry” (Harris and Isaac 1976). This industry is named after the 5 km long northeast trending ridge in the Koobi Fora region, which includes thousands of Developed Oldowan stone artifacts. The sites are well bounded by a series of volcanic ashes that provide a relatively high-resolution chronostratigraphy (McDougall and Brown 2006).

The Karari Industry is limited to the Okote member of the Koobi Fora Formation, which is bounded by the Okote tuff complex and the Chari tuff and thus is well dated to between 1.57 and 1.37 Ma. Here, we report on a series of landscape-scale excavations conducted by Rogers (1997). These excavations are particularly useful for studying landscape-scale interactions between hominins and their environments because Rogers linked all of his excavations to a single datum. This allows the investigation of a single land surface over several kilometers of outcrop (Fig. 7.1). In addition Rogers’ study also linked his excavation to the stratigraphic levels in previously excavated localities (those excavated by Harris: Harris and Isaac 1997), which allows the expansion of the sample sizes for a landscape study. Table 7.1 describes the sample sizes for each separate excavation in this study. Sample sizes range dramatically. In our analysis, samples are combined into groups based on paleogeographic settings (Table 7.1, Fig. 7.1). The vast majority of the collections used in this study are derived from collections found in Koobi Fora paleontological Area 130. However, a subset of single platform cores is derived from Area 131 further to the south in the Karari ridge area. This area was selected because sedimentological context of these sites suggests that they were extremely distal to any of the river systems that dominate Area 130. It is assumed that these sites are highlands between river valleys such as the one recorded in geological sections in Area 130 (Feibel 1988). One thing that can be certain is that large clasts like the ones used as blanks for single platform cores were completely absent from the paleogeographic setting of Area 131 (Braun et al. 2008a). Thus, we can use the different paleogeographic settings as proxies for the availability of raw material. Sites closer to the channel system in Area 130 have greater availability of raw material. Paleogeographic settings further from the channel would have had lower availability of raw material. This variation in raw material availability allows us to study the decisions that hominins made regarding the transport and discard of stone artifacts.

Recently, Brantingham and others (Brantingham 2003; Brantingham et al. 2006; Wilson 2007) have used advanced mathematical models to predict the movement of raw material over a landscape. These models provide predictions for the archaeological expression of the presence of hominin selection in transport and discard of stone. Although for many archaeologists, the classic distance–decay model suggests curation of “higher quality” raw materials, the neutral model suggests that this pattern can actually be generated without any selection at all. If the archaeological record matches the neutral model, then we can be sure that hominin transport decisions are not significantly different from purely random selection and discard behaviors. However, deviations from the neutral model will allow us to understand the nature of hominin raw material procurement and discard decisions. Many models of the distance–decay relationship associated with distance to raw materials rely on the frequency of artifacts of particular “nonlocal” raw materials within an assemblage

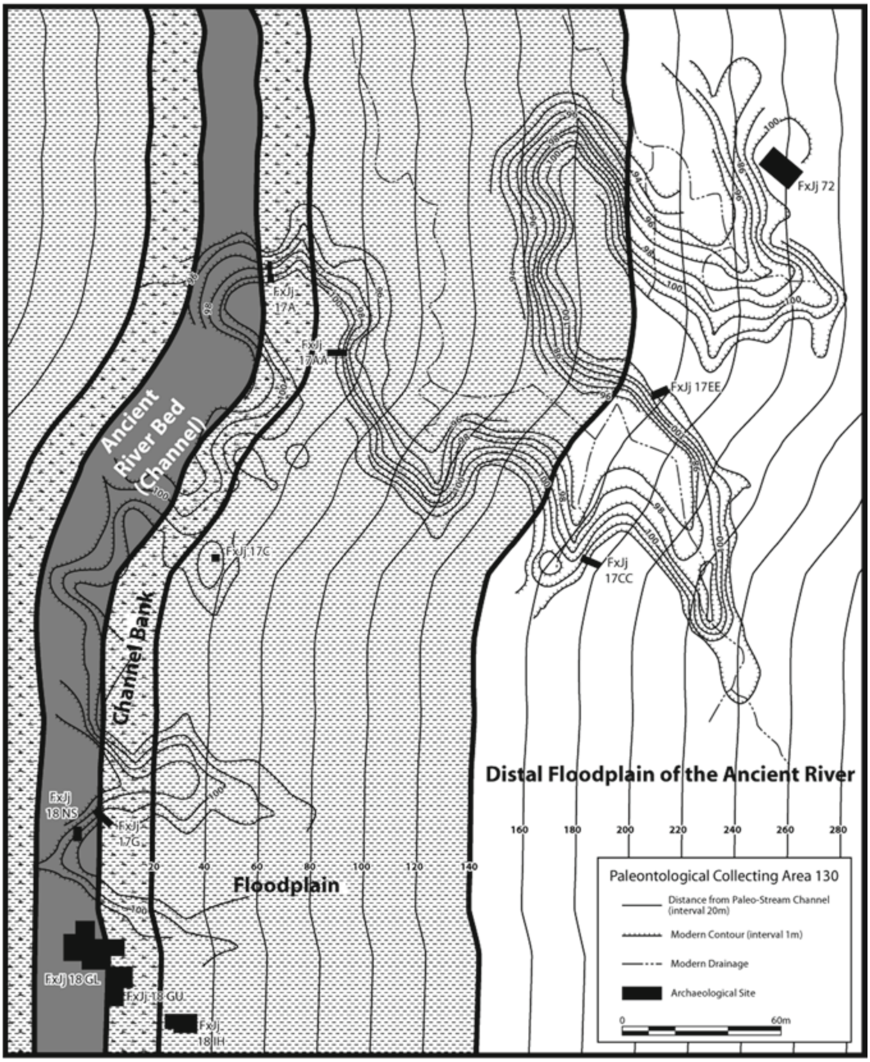

Fig. 7.1 Map of the landscape-scale excavations conducted by Rogers (1997) and Harris (1978). *Contour lines* are based on an arbitrary datum. Paleogeographic distinctions are based on sedimentological characteristics of the excavations. For further details refer to Rogers (1997) and Braun et al. (2008a, b, c). Redrawn from Braun et al. (2008)

(Blumenschine et al. 2008). However, the use of frequency measures assumes that each artifact has a similar use-life. This is an assumption that may not be valid (Ammerman and Feldman 1974; Shott 1989, 1998). In this study, we use models of curation that are based on unifacial reduction as a proxy for the amount of work a particular tool has done prior to discard (Shott 1989).

Table 7.1 Sites included in this study and the number of single platform cores found in each one of these sites

Locality	Paleogeographic reconstruction	Excavator	Single platform cores (*n*)
FxJj 18 GL	Channel	JWKH	38
FxJj 18 NS	Channel	JWKH	12
FxJj 18 GU	Channel bank	JWKH	7
FxJj 17 G	Channel bank	MJR	4
FxJj 18 IH	Proximal floodplain	JWKH	45
FxJj 17 AA	Proximal floodplain	MJR	2
FxJj 17 EE	Distal floodplain	MJR	12
FxJj 17 CC	Distal floodplain	MJR	3
FxJj 72	Distal floodplain	MJR	19
FxJj 20 E	Inland	JWKH	10
FxJj 20 M	Inland	JWKH	18

Methodology

Recently, there has been intense investigation into the most secure method for calculating the degree of reduction in unifacial tools (Eren et al. 2005; Eren and Sampson 2009; Hiscock and Attenbrow 2003; Hiscock and Clarkson 2005, 2009). Dibble's method of calculating the original size of a flake from platform attributes (Dibble 1987, 1995) has received less investigation lately because of the increase in interest in versions of Kuhn's geometric index of unifacial reduction (Hiscock and Clarkson 2005; Kuhn 1990). Dibble's method, which largely compared the size of the platform to the size of the reduced tool as a proxy for reduction has been criticized on several fronts (Davis and Shea 1998). The most notable of these was the seeming miscalculations associated with predicting the original size of a flake prior to retouch. However, these miscalculations were mostly the result of the poor estimation of platform size (usually calculated as platform length by platform width) (Shott et al. 2000). Previously, we have shown that enhanced digital image techniques increases the prediction power of platform attributes (Braun et al. 2008b). Yet these digital image assessments are based entirely on one dimensional measures of a complex three-dimensional object. Here, we utilize a Microscribe (Immersion Corp) to collect three-dimensional points on the platforms of single platform cores. These cores are large unifacial flakes that are reduced by using the ventral surface of the flake as a flaking platform for the removal of subsequent smaller flakes (Harris 1978; Ludwig and Harris 1998). These three-dimensional points are then used to calculate a triangulated integrated network (Fig. 7.2). The three-dimensional points captured from the surface of platforms usually encompass between 15 and 20 points around the perimeter of the platform, as well as several points inside this perimeter. More work is needed to determine exactly how many points are needed to accurately capture platform area. These three-dimensional surfaces can be used to calculate surface area. We use software originally developed for mapping applications (ESRI ArcGIS) to calculate triangulated integrated networks

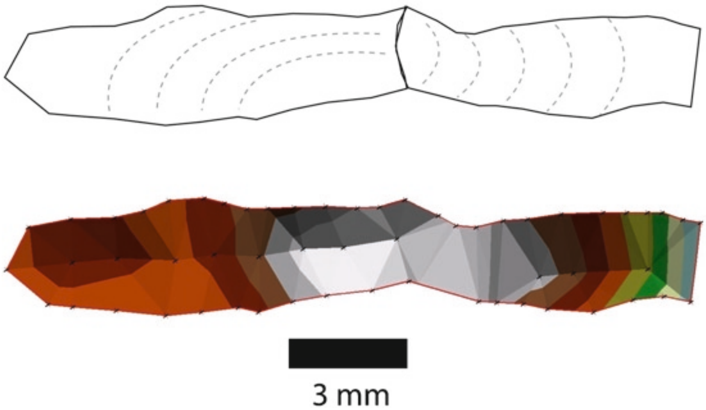

Fig. 7.2 An example of a triangulated integrated network surface of a platform

based on the coordinates of the points collected from the surface of the platform. The calculated triangulated integrated networks must first be clipped to the perimeter of the platform by first creating a polygon of the two-dimensional outline of the platform. Then using algorithms provided by ArcGIS (ESRI), surface area within the polygon can be calculated using the lowest height measured as the base height. Three-dimensional values must be captured in centimeters, and we found that having all the values in positive numbers allows for easy calculation of the surface area. This allows the assessment of the surface of platforms to more accurately predict flake size from platform attributes. We tested this method on a series of experimentally produced whole flakes. The flakes were from a series of reduction experiments conducted on cobbles made from the same Gombe Basalt that is used in the Okote Member of the Koobi Fora Formation. We selected a series of 35 flakes that represented the full range of sizes and shapes from two cobble reduction experiments previously described (Braun et al. 2008c).

Results

The three-dimensional techniques show that platform attributes can very easily predict the size of a flake (Fig. 7.3). The prediction of flake size is strongest when logarithmically transformed data is used in the regression models (Shott et al. 2000). The variation in platform surface area can predict 87% of the variation in flake mass. Interestingly, this is true for flakes of small mass (e.g., 1.3 g) and relatively large mass (e.g., 352 g). Therefore, we can be reasonably confident that the estimations of original flake size of single platform cores are accurate enough to use them to predict the degree of reduction. It should be noted that the strength of the relationship between platform surface area and flake size is better than previous estimations using caliper measurements ($r^2 = 0.67$; Shott et al. 2000); however, they

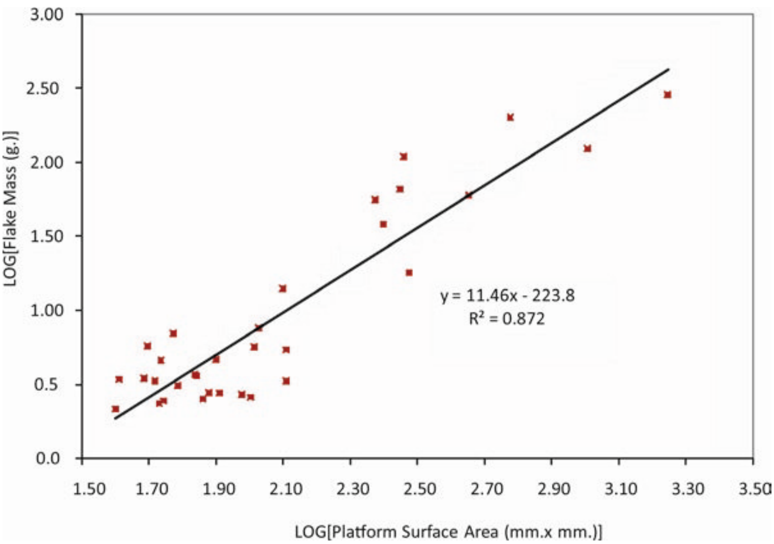

Fig. 7.3 Regression of logarithmically transformed flake mass against logarithmically transformed platform surface area in a subset of whole flakes from the Okote member of the Koobi Fora Formation

represent only minimal increases in the estimation of flake size over digital image methods ($r^2=0.86$; Braun et al. 2008b). This may be the result of platforms that are relatively flat in the Oldowan. However, application of this methodology may show dramatic increases in effectiveness in assemblages where platforms significantly deviate from flat surfaces (e.g., *chapeau de gendarme* platforms).

When reduction is estimated (based on a ratio of platform surface area to core mass), we can see that the early hominins clearly were showing trends toward more intensively using their cores in regions that had lower raw material variability (Fig. 7.4). However, it should be noted that there is extensive variation within each paleogeographic region, perhaps exacerbated by the relatively small distances between them. Previous analysis of similar data has shown significant differences in levels of reduction between these groups (Braun et al. 2008b).

Discussion

The data from the Developed Oldowan of the Koobi Fora region suggest that the distance–decay pattern that has previously been suggested to represent evidence of planning and systematic transport behavior (~curation) is present even in some of the earliest stone tool industries. However, as Brantingham (2003) has shown this pattern may actually be produced through a neutral model of transport. Brantingham's study suggests that because raw material from nonlocal sources have been in the

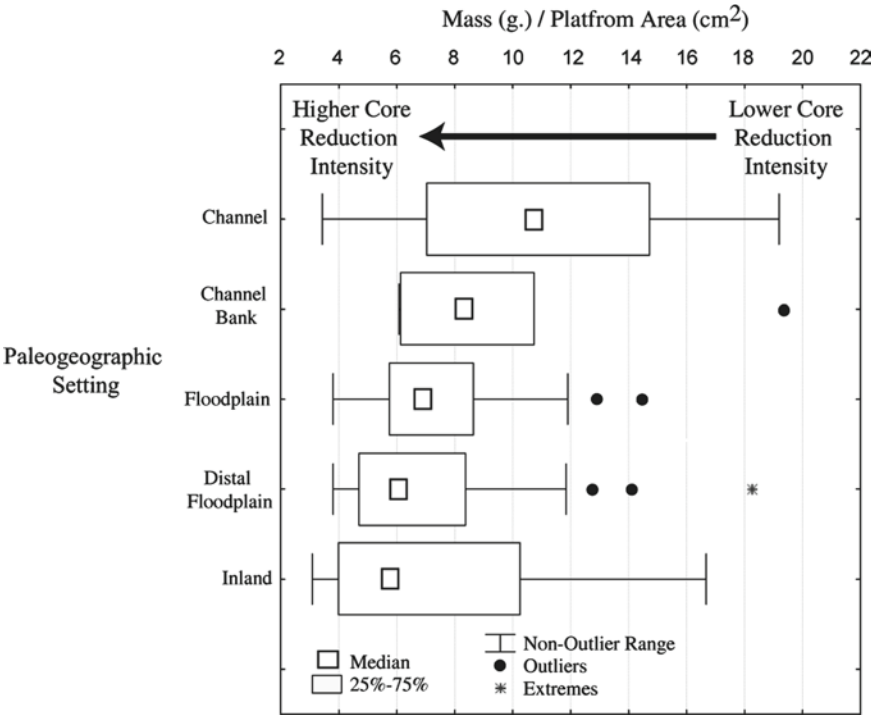

Fig. 7.4 Boxplot of calculated reduction levels (platform area/flake mass) for single platform cores from a variety of different paleogeographic settings

hominin tool kit for a longer period of time once they are discarded at locations distal to the raw material sources, and therefore, it should be expected that artifacts made from these raw materials will show extensive reduction. Brantingham's agent based model also suggests that variation in reduction will actually decrease as a hominin moves further from raw material sources (Fig. 7.5). In the Developed Oldowan assemblages, this expected pattern is not supported. In fact, the opposite pattern can be seen where artifacts discarded in areas most distal from resources (e.g., Inland paleogeographic setting) have the greatest amount of variation. This indicates that there were instances when hominins actually transported tools long distances (>3 km) with minimal reduction and similarly some cores were discarded very close to raw material sources after extensive reduction.

This variation in core reduction is displayed in the box plots in Fig. 7.4; however, this display of the distribution of the data may be masking more complex variations between paleogeographic settings. Shott and Sillitoe (2005) have suggested that since measures of reduction are actually measuring the degree of tool use-life, the distribution of these values should be treated like demographic statistics (e.g., age at death). Shott and Sillitoe (2004, 2005) developed a series of methods for interrogating the distribution of use-life data which allows for the calculation of curves that represent the percentage

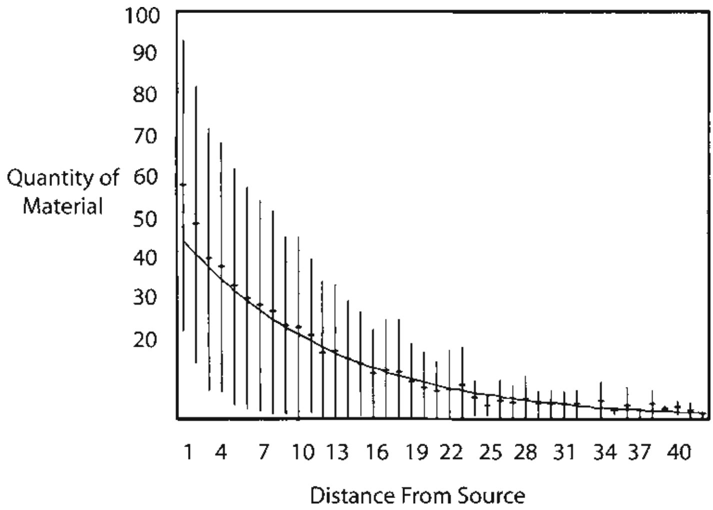

Fig. 7.5 Neutral model of distance and decay. Redrawn from Brantingham 2003

of the assemblage that was used to the fullest possible extent. Shott and Sillitoe (2003) referred to these curves as "curation curves," and they allow for a simple yet informative measure of the degree of curation represented by a particular assemblage. As the measure of reduction calculated in this study represents the percentage of the original size of the flake that has been removed by reduction, we can determine how much use-life was not extracted from these cores. In Fig. 7.6, we display the data from this study in the "channel" paleogeographic setting in multiple different panels showing the development of a curation curve (Fig. 7.6a–d). Shott and Sillitoe (2003, 2005) have also applied their data to various statistical methods originally developed in demographic analysis that describe the shape of cumulative percentile graphs. They found that the Gompertz–Makeham "b" parameter is the most appropriate measure of assessing these curation curves (Fig. 7.7). In the last panel, we represent two extremes of a highly curated assemblage and an assemblage which shows no evidence of curation. The assemblage with the very high Gompertz–Makeham "b" parameter would have an entire assemblage of cores that were reduced to the maximum possible extent (i.e., 100% of the assemblage was reduced to less than 10% of the original mass). At the opposite extreme, a very low level of curation is represented by the assemblage with a very low Gompertz–Makeham "b" parameter. In this assemblage, many of the cores would have not been reduced at all, and many of the cores would only have been reduced to 80% of their original prereduction mass. The Gompertz–Makeham "b" parameter was calculated using WinModest based on the methodology described in Shott and Sillitoe (2004).

The different paleogeographic settings in this study show drastically different curation curves. Although the inland setting showed great variation in the degree of reduction of tools, we can see that upwards of 50% of the assemblage had been reduced to the extent that less than 40% of the original mass was left when the core was discarded. This contrasts markedly with the channel setting, which shows that

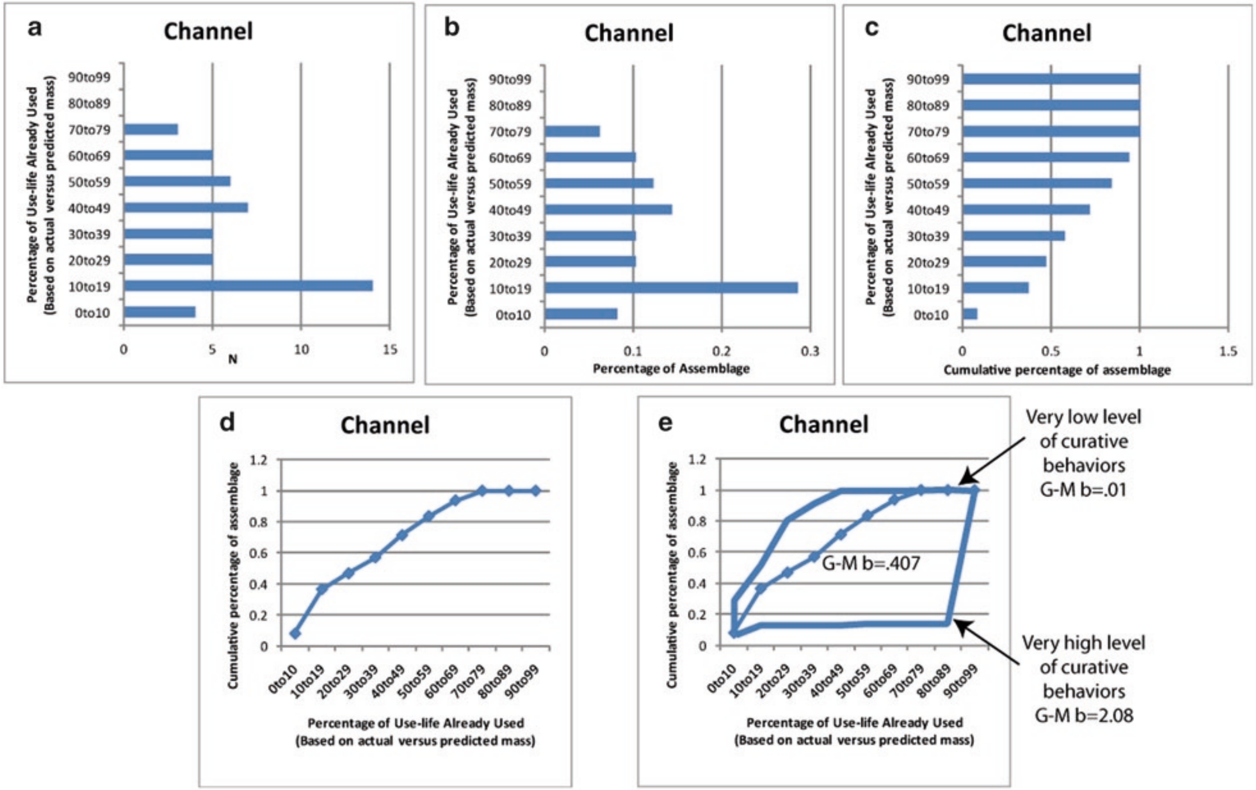

Fig. 7.6 The development of a curation curve. (**a**) The distribution of cores from the channel paleogeographic context within ten categories representing the amount of reduction recorded based on the prediction of the original size of the core using platform measurements. (**b**) The same distribution as (**a**), but represented as a percentage of the assemblage. (**c**) The same data as found in *panels* (**a** and **b**) but displayed as a cumulative percentage. (**d**) The same cumulative percentage found in *panel* **c** but represented as a "curation curve" (**e**) This panel displays the description of two extremes of curative behaviors and their associated Gompertz–Makeham "b" parameters. For further information on "curation curves" see Shott and Sillitoe (2003, 2005)

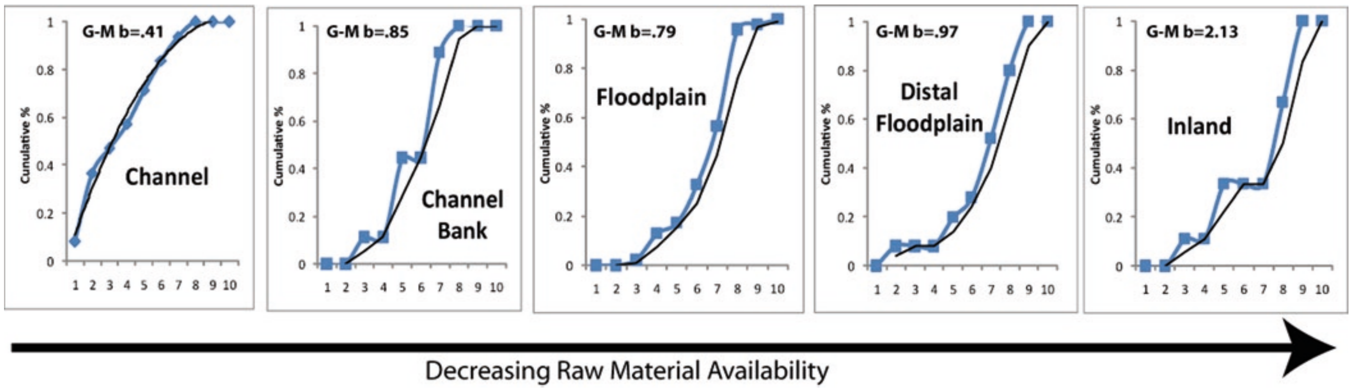

Fig. 7.7 Curation curves and associated Gompertz–Makeham "b" parameters for the paleogeographic settings in this study

more than 50% of the assemblage was discarded with more than 70% of the usable core volume untouched. The values of the Gompertz–Makeham “b” parameter also shows this difference with a relative increase in this parameter in paleogeographic settings that are further from raw material sources. However, there is not a one-to-one correlation between raw material variability and Gompertz–Makeham “b” and it seems as if there were many cores that were reduced rather extensively in the channel bank setting. It is likely that the variation in stone tool-mediated resources across the ancient landscape influenced the level of core reduction across the transect from channel bank to inland highlands. In areas where more resources were encountered, hominins would likely have reduced their cores more extensively. The end result is assemblages that show higher levels of curation. However important the distribution of stone tool-mediated resources was, it does not appear to be as vital to discard decisions as the availability of raw material as is evinced by the very high Gompertz–Makeham “b” values in the inland setting.

Conclusion

This study capitalizes on new methods of capturing stone artifact morphology to enhance the prediction of flake mass in large cores from the Developed Oldowan. Building upon this enhanced methodology for calculating flake size, it is possible to then expand the analysis to look at models of artifact transport and curation. Using models constructed from agent-based modeling and employing methods that have been borrowed from demographic analysis, it is possible to show that hominins from the Pleistocene of the Turkana Basin made decisions about when to discard tools based not only on the distance to raw material sources but also on the requirement for stone artifacts in different settings. This indicates that even Oldowan technology may represent an understanding of the landscape-scale distribution of resources that is not usually associated with these early tool makers.

Although this study represents the use of new methods (e.g., three-dimensional capture of artifact morphology), it also builds upon models previously applied to Middle Paleolithic industries from Europe (Dibble 1995) as well as ethnographic evidence (Binford 1980; Shott and Sillitoe 2005; Shott and Weedman 2007). This underscores the basic tenets that chipped stone assemblages are very similar and there is a definite need for archaeologists who work with stone tools to begin to expand beyond the previous conventions of lithic analysis. Basic descriptive analyses of the types and shapes of stone artifacts are not sufficient to explain behavior using stone tools. Even the most basic of stone tool technologies do reflect information about the behavior (and possibly even the intelligence) of the toolmakers who made them. Currently, this information remains “untranslated” (Binford 1981). There is a need for lithic specialists to embrace the multitude of new technologies available to capture and interrogate variation in stone artifacts. There is certainly the possibility that some of these new innovations have very little to offer lithic anlaysis. As has been shown in this study, developing three-dimensional techniques to capture platform area does not

significantly affect the prediction of flake size from platform attributes. Yet the fact that both digital imaging techniques (Braun and Harris 2003) and three-dimensional techniques both increase the accuracy of the prediction of whole flakes from platform measurements suggests there is an internal consistency with these new methods. Further, the use of demographic techniques to interrogate the distribution of artifact morphology within different assemblages has certainly allowed us to view a part of Oldowan behavior that was previously “untranslated”.

References

Ammerman, A.J. and Feldman, M., 1974. On the ‘Making’ of an assemblage of stone tools. *American Antiquity* 39: 610–616.

Andrefsky, W.J., 2005. *Lithics: Macroscopic Approaches to Analysis*. Cambridge University Press, Cambridge.

Binford, L.R., 1981. *Bones: Ancient Men and Modern Myths*. Academic Press, New York.

Binford, L.R., 1979. Organization and formation processes: looking at curated technologies. *Journal of Anthropological Research* 35: 255–273.

Binford, L.R., 2001. Where do research problems come from? *American Antiquity* 66: 669–678.

Binford, L.R., 1980. Willow smoke and dogs’ tails: hunter-gatherer settlement systems and archaeological site formation. *American Antiquity* 45: 4–20.

Blumenschine, R., Masao, F.T., Tactikos, J. and Ebert, J., 2008. Effects of distance from stone source on landscape-scale variation in Oldowan artifact assemblages in the Paleo-Olduvai Basin, Tanzania. *Journal of Archaeological Science* 35: 76–86.

Brantingham, P.J., 2003. A neutral model of stone raw material procurement. *American Antiquity* 68: 487–509.

Brantingham, P.J., Eerkens, J., Feblot-Augustins, J., Haws, J., Shott, M., Turchin, P. and van Gijseghem, H., 2006. Measuring forager mobility. *Current Anthropology* 47: 435–459.

Braun, D.R., Harris, J. and Maina, D., 2008a. Oldowan raw material procurement and use: evidence from the Koobi Fora Formation. *Archaeometry* 51: 26–42.

Braun, D.R. and Harris, J.W.K., 2003. Technological developments in the Oldowan of Koobi Fora: Innovative techniques of artifact analysis. In *Oldowan: Rather More than Smashing Stones*, edited by J.M. Moreno, R.M. Torcal, and I.T. Sainz, pp. 117–144. University of Barcelona Press, Barcelona

Braun, D.R., Rogers, M.J., Harris, J.W.K. and Walker, S.J., 2008b. Landscape scale variation in hominin tool use: evidence from the Developed Oldowan. *Journal of Human Evolution* 55: 1053–1063.

Braun, D.R., Tactikos, J.C., Ferraro, J.V., Arnow, S.L. and Harris, J.W.K., 2008c. Oldowan reduction sequences: methodological considerations. *Journal of Archaeological Science* 35: 2153–2163.

Brown, F.H. and Feibel, C.S., 1986. Revision of lithostratigraphic nomenclature in the Koobi Fora region, Kenya. *Journal of the Geological Society* 143: 297–310.

Brumm, A., Aziz, F., Van den Bergh, G.D., Morwood, M.J., Moore, M.W., Kurniawan, I., Hobbs, D.R. and Fullagar, R., 2006. Early stone technology on Flores and its implications for *Homo floresiensis*. *Nature* 441: 624–628.

Clarkson, C., Vinicius, L., Lahr, M.M., 2006. Quantifying flake scar patterning on cores using 3D recording techniques. *Journal of Archaeological Science* 33: 132–142.

Davis, Z.J. and Shea, J.J., 1998. Quantifying lithic curation: an experimental test of Dibble and Pelcin’s original flake-tool mass predictor. *Journal of Archaeological Science* 25: 603–610.

de Heinzelin, J., Clark, J.D., White, T.D., Hart, W.S., Renne, P.R., Woldegabriel, G., Beyene, Y. and Vrba, E.S., 1999. Environment and behavior of 2.5-million-year-old Bouri hominids. *Science* 284: 625–629.

Dibble, H.L., 1998. Comment on 'Quantifying Lithic Curation, an Experimental Test of Dibble and Pelcin's Original Flake-Tool Mass Predictor', by Zachary J. Davis and John J. Shea. *Journal of Archaeological Science* 25: 611–613.

Dibble, H.L., 1987. Interpretation of middle Paleolithic scraper morphology. *American Antiquity* 52: 109–117.

Dibble, H.L., 1995. Middle Paleolithic scraper reduction: background, clarification, and review of the evidence to date. *Journal of Archaeological Method and Theory* 2: 299–368.

Eren, M.I., Dominguez-Rodrigo, M., Kuhn, S.L., Adler, D.S., Le, I. and Bar-Yosef, O., 2005. Defining and measuring reduction in unifacial stone tools. *Journal of Archaeological Science* 32: 1190–1201.

Eren, M.I. and Sampson, CG., 2009. Kuhn's geometric index of unifacial stone tool reduction (GIUR): does it measure missing flake mass? *Journal of Archaeological Science* 36(6): 1243–1247.

Feibel, C.S., 1988. *Paleoenvironments from the Koobi Fora Formation, Turkana Basin, Northern Kenya*. Department of Geology and Geophysics, University of Utah, Salt Lake City.

Feibel, C.S., Brown, F.H. and McDougall, I., 1989. Stratigraphic context of fossil hominids from the Omo group deposits: northern Turkana basin, Kenya and Ethiopia. *American Journal of Physical Anthropology* 78: 595–622.

Gowlett, J.A.J., 1986. Culture and conceptualisation: The Oldowan-Acheulian gradient. In *Stone Age Prehistory: Studies in Memory of Charles McBurney*, edited by G.N. Bailey and P. Callow, pp. 234–240. Cambridge University Press, Cambridge.

Harris, J.W.K., 1978. *The Karari Industry, Its Place in East African Prehistory*. Anthropology, University of California, Berkeley.

Harris, J.W.K. and Isaac, G.L., 1976. The Karari industry: early Pleistocene archaeological evidence from the terrain, east of Lake Turkana. *Nature* 262: 102–107.

Harris, J.W.K. and Isaac, G.L., 1997. Sites in the Upper KBS, Okote, and Chari members. In *Koobi Fora Research Project Vol. 5: Plio-Pleistocene Archaeology*, edited by G.L. Isaac, pp. 115–220. Clarendon Press, Oxford.

Hiscock, P. and Attenbrow, V., 2003. Early Australian implement variation: a reduction model. *Journal of Archaeological Science* 30: 239–249.

Hiscock, P. and Clarkson, C., 2005. Experimental evaluation of Kuhn's geometric index of reduction and the flat-flake problem. *Journal of Archaeological Science* 32: 1015–1022.

Hiscock, P. and Clarkson, C., 2009. The reality of reduction experiments and the GIUR: reply to Eren and Sampson. *Journal of Archaeological Science* 36(7): 1576–1581.

Kantner, J., 2008. The archaeology of regions: from discrete analytical toolkit to ubiquitous spatial perspective. *Journal of Archaeological Research* 16: 37–81.

Kimura, Y., 2002. Examining time, trends in the Oldowan technology at Beds I and II, Olduvai Gorge. *Journal of Human Evolution* 43: 291–321.

Kuhn, S., 1990. A geometric index of reduction for unifacial stone tools. *Journal of Archaeological Science* 17: 581–593.

Leakey, M.D., 1975. Cultural patterns in the Olduvai sequence. In *After the Australopithecines: Stratigraphy, Ecology and Culture Change in the Middle Pleistocene*, edited by K.W. Butzer and G.L. Isaac, pp. 477–493. Mouton, The Hague.

Ludwig, B.V., 1999. *A Technological Reassessment of East African Plio-Pleistocene Lithic Artifact Assemblages*. Anthropology, Rutgers University, New Brunswick.

Ludwig, B.V. and Harris, J.W.K., 1998. Towards a technological reassessment of East African Plio-Pleistocene lithic assemblages. In *The Rise and Diversity of the Lower Paleolithic*, edited by M. Petraglia and K. Paddaya, pp. 84–106. Academic Press, New York.

Lycett, S.J. and von Cramon-Taubadel, N., 2008. Acheulean variability and hominin dispersals: a model-bound approach. *Journal of Archaeological Science* 35: 553–562.

Lycett, S.J., von Cramon-Taubadel, N. and Foley, R., 2006. A crossbeam co-ordinate caliper for morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33: 847–861.

McDougall, I. and Brown, F.H., 2006. Precise Ar-40/Ar-39 geochronology for the upper Koobi Fora formation, Turkana Basin, northern Kenya. *Journal of the Geological Society* 163: 205–220.

Newcomer, M., Grace, R. and Unger-Hamilton, R., 1986. Investigating microwear polishes with blind tests. *Journal of Archaeological Science* 13: 203–217.

Odell, G.H., 1996. Economizing behavior and the concept of "Curation". In *Stone Tools: Theoretical Insights into Human Prehistory*, edited by G.H. Odell, pp. 51–80. Plenum Press, New York.

Richtsmeier, J.T., Deleon, V.B. and Lele, S.R., 2002. The promise of geometric morphometrics. *Yearbook of Physical Anthropology* 45: 63–91.

Rogers, M.J., 1997. *A Landscape Archaeological Study at East Turkana, Kenya*. Anthropology, Rutgers University, New Brunswick.

Rogers, M.J., Harris, J.W.K. and Feibel, C.S., 1994. Changing patterns of land-use by Plio-Pleistocene Hominids in the Lake Turkana Basin. *Journal of Human Evolution* 27: 139–158.

Shott, M.J., 1996. An exegesis of the curation concept. *Journal of Anthropological Research* 52: 259–280.

Shott, M.J., 1989. On tool-class use lives and the formation of archaeological assemblages. *American Antiquity* 54: 9–30.

Shott, M.J., 1998. Status and role of formation theory in contemporary archaeological practice. *Journal of Archaeological Research* 6: 299–329.

Shott, M.J., 2002. Weibull estimation on use life distribution in experimental spear-point data. *Lithic Technology* 27: 93–109.

Shott, M.J. and Ballenger, J.A.M., 2007. Biface reduction and the measurement of dalton curation: a southeastern United States case study. *American Antiquity* 72: 153–175.

Shott, M.J., Bradbury, A.P., Carr, P.J. and Odell, G.H., 2000. Flake size from platform attributes: predictive and empirical approaches. *Journal of Archaeological Science* 27: 877–894.

Shott, M.J. and Sillitoe, P., 2001. The mortality of things: correlates of use life in Wola material culture using age-at-census data. *Journal of Archaeological Method and Theory* 8: 269–302.

Shott, M.J. and Sillitoe, P., 2004. Modeling use-life distributions in archaeology using New Guinea Wola ethnographic data. *American Antiquity* 69: 339–355.

Shott, M.J. and Sillitoe, P., 2005. Use life and curation in New Guinea experimental used flakes. *Journal of Archaeological Science* 32: 653–663.

Shott, M.J. and Weedman, K.J., 2007. Measuring reduction in stone tools: an ethnoarchaeological study of Gamo hidescrapers from Ethiopia. *Journal of Archaeological Science* 34: 1016–1035.

Stout, D. and Chaminade, T., 2007. The evolutionary neuroscience of tool making. *Neuropsychologia* 45: 1091–1100.

Stout, D., Toth, N., Schick, K. and Chaminade, T., 2008. Neural correlates of Early Stone Age toolmaking: technology, language and cognition in human evolution. *Philosophical Transactions of the Royal Society B: Biological Sciences* 363: 1939–1949.

Stout, D., Toth, N., Schick, K.D., Stout, J. and Hutchins, G., 2000. Stone tool-making and brain activation: position emission tomography (PET) studies. *Journal of Archaeological Science* 27: 1215–1223.

Wilson, L., 2007. Understanding prehistoric lithic raw material selection: application of a gravity model. *Journal of Archaeological Method and Theory* 14: 388–411.

Chapter 8
The Mathematics of Chaînes Opératoires

P. Jeffrey Brantingham

Abstract The decision-making processes underlying core reduction are often framed in terms of the execution of different complex, integrated technological designs. This chapter adopts an alternative approach of specifying simple, independent technological decisions deployed during reduction. These are used to develop three mathematical models of core reduction of increasing complexity. The modeled technologies are labeled as Bernoulli, Markov, and Price cores after their fundamental mathematical properties. Expectations concerning core reduction intensity are derived and tested using data from Paleolithic sites in Africa and Asia.

Introduction

Many inferences about Paleolithic behavior, culture, adaptation, and hominin cognitive capacities hinge on the analysis of stone technological design. In general, the number of technological actions involved in core reduction, the orders in which they are deployed, and the ways in which they are combined are taken as proxy measures of such things as time, energy, or risk optimization in foraging (Beck et al. 2002; Kuhn 1994; Nelson 1991), cultural transmission (Kuhn 2004; Lycett 2008), and planning depth or spatial cognitive modules (Delagnes and Roche 2005). However, any sizable archaeological assemblage usually contains cores and debitage representing tremendous variability in the intensity of reduction; some cores are intensively reduced and discarded in "spent" condition, while other cores discarded seemingly with abundant remaining use life. Idealized technological designs are therefore implemented with tremendous variability and, it is fair to say, many behavioral, adaptive, and cognitive models of hominin behavior have not taken the variability in core reduction sufficiently into account. Here, I seek a formalization of the processes leading to variability in core reduction intensity and, ultimately, core design.

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Bernoulli Core Technology

At an elementary level, the process of stone core reduction consists of directing force at a mass of stone to remove a sharp-edged "flake" (detached piece) that may then be used in one or more activities. The detached piece of stone is presumed to have economic utility, which may be measured in a number of interdependent currencies including product shape (Boëda 1995; Elston and Brantingham 2003), weight (Beck et al. 2002; Kuhn 1994), edge length (Brantingham and Kuhn 2001), or resharpening potential (Bamforth 2002; Dibble 1995). As a simple starting point, core reduction may be modeled as a series of Bernoulli trials, where each detached piece removed from the core either meets a predetermined utility criterion (i.e., a success) or it does not (i.e., a failure). This model requires that the probability of producing a detached piece meeting the utility criterion is fixed, usually endogenously, and that each removal is independent of both the preceding and any subsequent removals. Under these conditions, the process of core reduction is completely specified by the negative binomial distribution.

$$P(N = X) = \binom{N-1}{n-1} p^n (1-p)^{N-n}, \tag{8.1}$$

where N is the number of flake removals necessary to produce n detached pieces meeting the utility criterion and p is the independent probability of producing an acceptable product with each attempted removal. For example, given a probability of success in any given flake removal attempt $p=0.6$, then Eq. 8.1 indicates that the probability of producing 18 acceptable products in 20 total removals is $P(N=20)=0.09$. The probability of a success p in this context may be interpreted as a measure of raw material quality.

Mean core reduction intensity is given by $\mu=n/p$, while the variance is given by $\sigma^2=n(1-p)/p^2$. Surprisingly, neither of these quantities are dependent upon the maximum number of flakes that can be removed from a core, though maximum use life is an implicit benchmark in many economic analyses of core reduction and is assumed to be an influence on reduction intensity (Brantingham and Kuhn 2001; Braun et al. 2008; Dibble and Bar-Yosef 1995). In the Bernoulli core model, the mean and variance in expected reduction intensity are dependent *only* upon the endogenous probability of a success p and the number of successful products n sought, which may be much less (or much more) than the maximum possible products N that could be produced by a core.

The Bernoulli core model predicts that mean core reduction intensity increases as the probability of a success decreases. Consider a hypothetical assemblage of cores, based on different raw material types, all of which are directed at producing a minimum of ten successful products (Fig. 8.1a). Cores based on the high-quality raw material, which has an endogenous probability of producing a successful flake $p=0.7$, are expected to have a mean reduction intensity of 14.29 removals. In contrast, cores based on the intermediate quality raw material ($p=0.5$) are expected

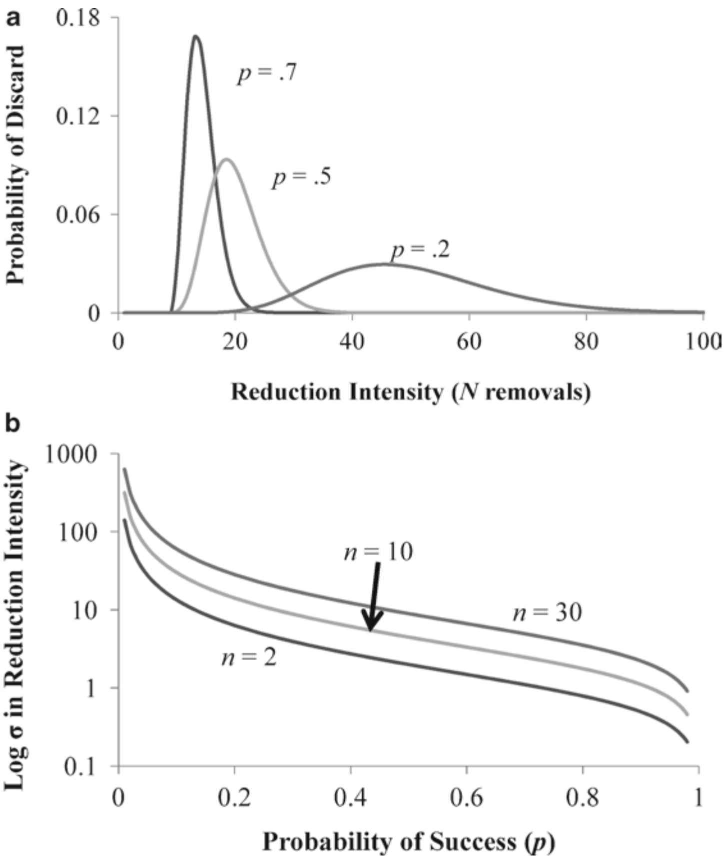

Fig. 8.1 (**a**) Raw materials characterized by high probabilities of success (i.e., low probability of reduction errors) will display low mean reduction intensity. Illustrated are the probability distributions for the total number of flakes removed N from a core at the point when ten successful flakes n are produced (and the core is discarded). Note that the expected mean reduction intensity n/p coincides with the mode only when the distribution is normal. (**b**) The standard deviation (σ) in core reduction intensity decreases geometrically as the probability of successful flake production increases. Illustrated are three curves for different values of n, the number of desired successes

to have a mean reduction intensity of 20 removals. The expected mean reduction intensity for cores based on the lowest quality material ($p = 0.2$) is 50 removals.

The Bernoulli core model also predicts that the standard deviation (σ) in core reduction intensity should decrease rapidly as the probability of success increases (Fig. 8.1b). For example, to obtain ten ($n = 10$) successful products, the standard deviation in core reduction intensity of a Bernoulli core is 30 removals ($\sigma^2 = 900$ removals^2) for a stone raw materials with a low endogenous probability of success $p = 0.1$. A standard deviation of only 1.77 removals ($\sigma^2 = 3.125$ removals^2) is expected for a raw material with a high endogenous probability of success $p = 0.8$.

Evaluating the Bernoulli Core Model

The Bernoulli core model is perhaps best suited to describing reduction intensity in relatively simple core technologies such as Oldowan (Mode I) core-and-flake industries. In particular, one might assume with Oldowan technologies that the probability of producing a successful flake is determined almost entirely by raw material quality (Potts 1991; Stout et al. 2005; Toth 1982). It also may be reasonable to assume that the successful production of an acceptable end product is largely independent of the results of earlier removals, and does not significantly influence the success of subsequent removals (but see Delagnes and Roche 2005). Oldowan (Mode I) core technologies thus may meet the two key assumptions necessary to model core reduction as a series of independent Bernoulli trials.

Figure 8.2 presents boxplots of weight-standardized core flake scar counts, by raw material class, for nine sites located in Olduvai Gorge Bed I and lower Bed II (Kimura 2002). The sites range in age from approximately 1.8 (DK) to 1.2 mya (TK) and include both classic Oldowan and early Acheulean industries. The raw material classes presented are aggregates of several distinct types. Quartz and quartzite materials are combined and generally are considered to be low quality (i.e., low p) because of a tendency for the material to fracture along internal cleavage planes. Fine-grained igneous materials include vesicular lava, phonolite, and basaltic lava. These materials can vary widely in quality depending upon the size and distribution of vesicles and phenocrysts in the rock matrix. When they are relatively fine-grained they are considered to be of intermediate quality (i.e., intermediate p). Finally, fine-grained siliceous rocks such as chert have the highest quality (i.e., highest p) relative to the other materials found in the Oldowan assemblages under consideration. Other stone raw materials present in the Oldowan assemblages such as gneiss are too rare to warrant statistical comparison.

If the assumptions concerning raw material quality are approximately correct, then the Bernoulli core model predicts that the mean and variance in reduction intensity should be lowest for the highest quality materials and, conversely, highest for the lowest quality materials. The data from Olduvai Bed I and II provide at best marginal support for the Bernoulli core model. Considering quartz/quartzite and lava raw materials, core reduction intensity patterns may be as anticipated; lower quality quartz/quartzite cores display both a greater median and greater range of flake scars per gram of raw material compared with the (somewhat) higher-quality lavas (Fig. 8.2). Patterns of core reduction intensity for chert cores, however, fail to conform to predictions. In all but one case (MNK Chert Factory Site), chert cores display both the greatest median and greatest range in reduction intensity of the materials present at the sites.

The reasons for the mixed performance of the Bernoulli core model are twofold. First, the model assumes that a core will be immediately discarded once the target number of acceptable flakes is reached. Second, if the target number of flakes has not been reached, then it is assumed that core reduction will continue even though the core might have little hope of ever producing them. Referring back to Fig. 8.1a,

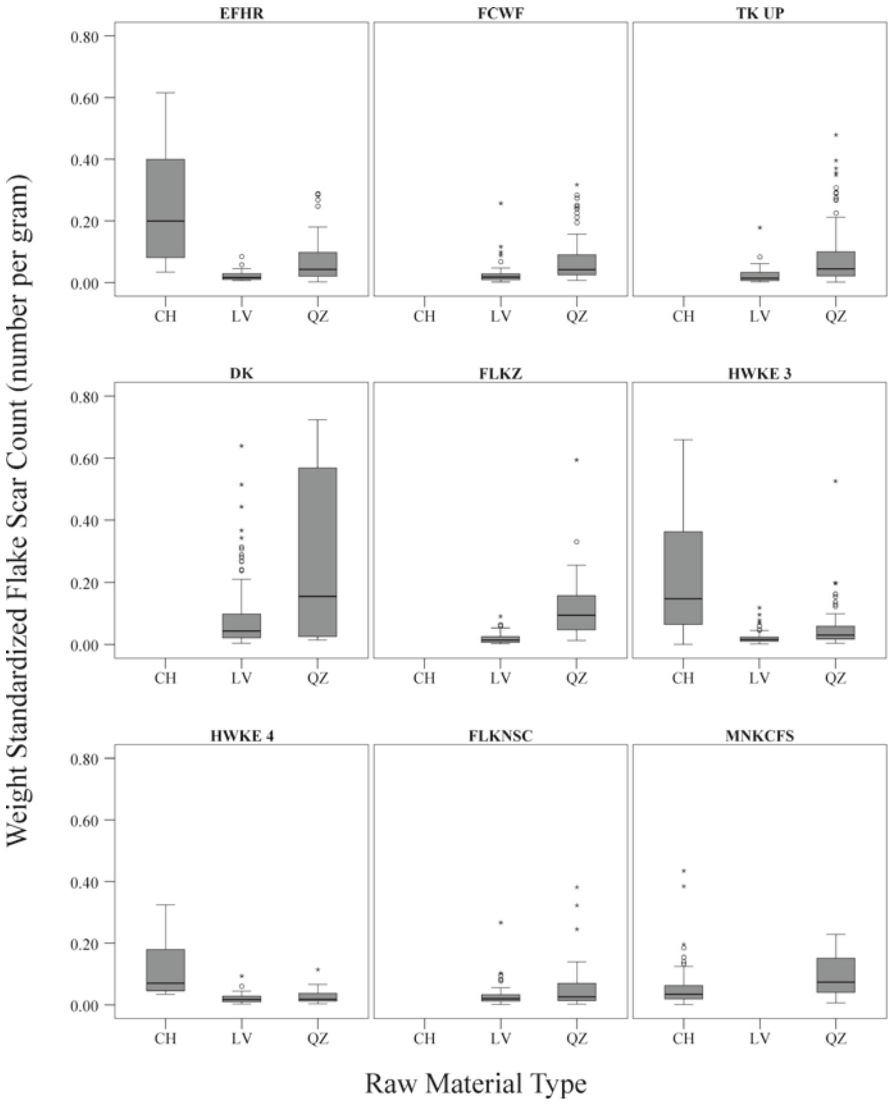

Fig. 8.2 The Bernoulli core model shows mixed results in predicting patterns of Oldowan core reduction intensity. Illustrated are the median, quartiles, and outliers for weight-standardized flake scar counts for Oldowan cores made on three broad types of stone raw material. Raw material quality (i.e., *p*) is generally lowest for quartz/quartzite, somewhat higher for lava materials and is highest for chert. The median and range of core reduction intensity for quartz/quartzite cores is greater than that for lava-based cores, corresponding to the predictions of the Bernoulli core model. However, the median and range of chert core reduction intensity is higher in all but one case, contrary to model prediction. The sample includes nine Olduvai Bed I and Bed II sites. Statistical summaries are based on Kimura (1999, 2002) and additional unpublished data provided by Yuki Kimura

it is now clear why mean reduction intensities increase as the probability of success decreases: Cores based on materials that have a high endogenous probability of success very quickly reach the target utility and are immediately discarded, whereas reduction continues blindly for core-based materials with a low probability of success. These assumptions are clearly flawed. Indeed, the opposite relationships are commonly assumed, namely, that high-quality raw materials will be intensively reduced to extract as many "successes" as possible, whereas low-quality materials will be abandoned at the first possible opportunity.

Markov Core Technology

When should one stop investing in the reduction of a specific stone core? This economic decision is integral to the process of stone core reduction. Unfortunately, such decisions – commonly termed as optimal stopping problems – turn out to be much more complex than they first appear (e.g., Dixit and Pindyck 1994). The complexities underlying the decision of when to stop core reduction stem from the fact that stone raw material fracture is inherently unpredictable: A core that has *so far* proven to be unproductive might eventually reverse this trend and end up by yielding a high return on the investment. In contrast, a core that has *so far* proven to be productive might suddenly become unworkable following a quick succession of reduction errors.

To model the decisions involved in core reduction under these conditions of uncertainty, it is necessary to make different assumptions about the nature of flake production. In contrast to the Bernoulli core model, where I assumed that utility of a removed product was independent of the results of all preceding removals, here I assume that the utilities of detached pieces are sequentially correlated.

$$x_{n+1} = x_n + \delta_n, \tag{8.2}$$

where x_n is the utility of the flake produced at reduction step n in a sequence of N possible removals, x_{n+1} is the utility of next flake in the sequence, and δ_n is a random error (variable) that occurs in the production of the flake at step $n+1$. Note that δ_n may be drawn from any number of different probability density functions. Equation 8.2 describes a simple Markov process where the probability of obtaining a particular utility x_{n+1} is dependent only upon: (1) the results of the event immediately preceding it x_n and (2) the nature of the stochastic process described by the random variable δ.

All future states of the system can be predicted if one understands the stochastic process δ and provided that even a single point x_n is known. Consider the situation where there is no error associated with flake production (i.e., $\delta = 0$). The utility achieved with the first removal x_1 is perfectly translated into the utility of the second removal x_2 and, in fact, all subsequent removals, until the core is finally discarded. Ideally, just this sort of "error free" process describes the economic principle behind stone blade technologies; each blade removed sets up the linear ridges that determine the size and shape

of all subsequent removals (Boëda 1995). Yet, situations where $\delta \sim 0$ are probably very rare. Even the most rigorously controlled knapping experiments demonstrate the there is always uncertainty inherent in flake production (Pelcin 1997).

The statistical distribution of errors produced during Markov core reduction may be modeled in a number of different ways. Here, I adopt a model where δ_n can assume one of two values.

$$\delta_n = \begin{cases} +\varepsilon, & p \\ -\varepsilon, & (1-p) \end{cases}. \tag{8.3}$$

Equation 8.3 states that positive errors of size $+\varepsilon$ occur with probability p, whereas negative errors of size $-\varepsilon$ occur with probability $1-p$. Positive errors may be interpreted as unexpected events in flake production that *increase* the utility of the detached product and potentially enhance the utility of subsequent products; sometimes overshooting the core margin not only yields a blade with a longer than expected cutting edge, but also establishes strong core convexities that allow one to remove even longer blades with the next blow. Negative errors, in contrast, are understood to be unexpected events in flake production (e.g., hinge or step fractures) yielding a product of low utility and which may negatively impact the expected utility of future products removed from the core. As with the Bernoulli core model, the probability of a success p may be interpreted as a measure of raw material quality.

Figure 8.3 illustrates how the probability of successful flake production p impacts the process of core reduction. Each panel shows core reduction trajectories simulated by iterating Eq. 8.2 for 100 steps (i.e., flake removals). In all cases, core reduction begins at an utility of zero arbitrary units (AU) (i.e., $x_0 = 0$) and the size of errors is set at $\varepsilon = 0.5$ AU. The only parameter allowed to vary is the probability of success p. Not surprisingly, when p is high the utility of products tends to increase over the course of core reduction (Fig. 8.3a), whereas the utility of products tends to decrease when p is low (Fig. 8.3b). Despite these general trends, there remains substantial variability in the trajectories followed by individual Markov cores. The mean utility of a collection of products derived from Markov cores after n removals is given by $\mu[x_n] = (p-q)\varepsilon n$, where $q = (1-p)$. The variance is given by $\sigma^2[x_n] = 4p(1-p)\varepsilon^2 n$ (Dixit and Pindyck 1994). For example, the expected mean utility of a collection of core products after 100 removals and with $p = 0.8$ is $\mu[x_{100}] = 30$ AU (Fig. 8.3a). The standard deviation in utility for this same collection of products after 100 removals is $\sigma = 4$ AU ($\sigma^2[x_{100}] = 16$ AU^2). The greatest uncertainty in core reduction occurs when $p = 0.5$, which may be interpreted to mean raw materials of intermediate quality. In this case, the products from different core reduction trajectories are expected to have a mean utility after 100 removals of $\mu[x_{100}] = 0$, the same as the initial starting utility, but the standard deviation is $\sigma = 5$ AU ($\sigma^2[x_{100}] = 25$ AU^2) (Fig. 8.3c).

Figure 8.3 also illustrates a key property of Markov processes: If the utility of the current detached piece is high, then the utility of the next piece will also tend to be high, and *vice versa*. This property has predictive value and therefore may be used in coming to a decision about whether to discard a core midway through reduction. In general terms, Markov core reduction should be terminated when the

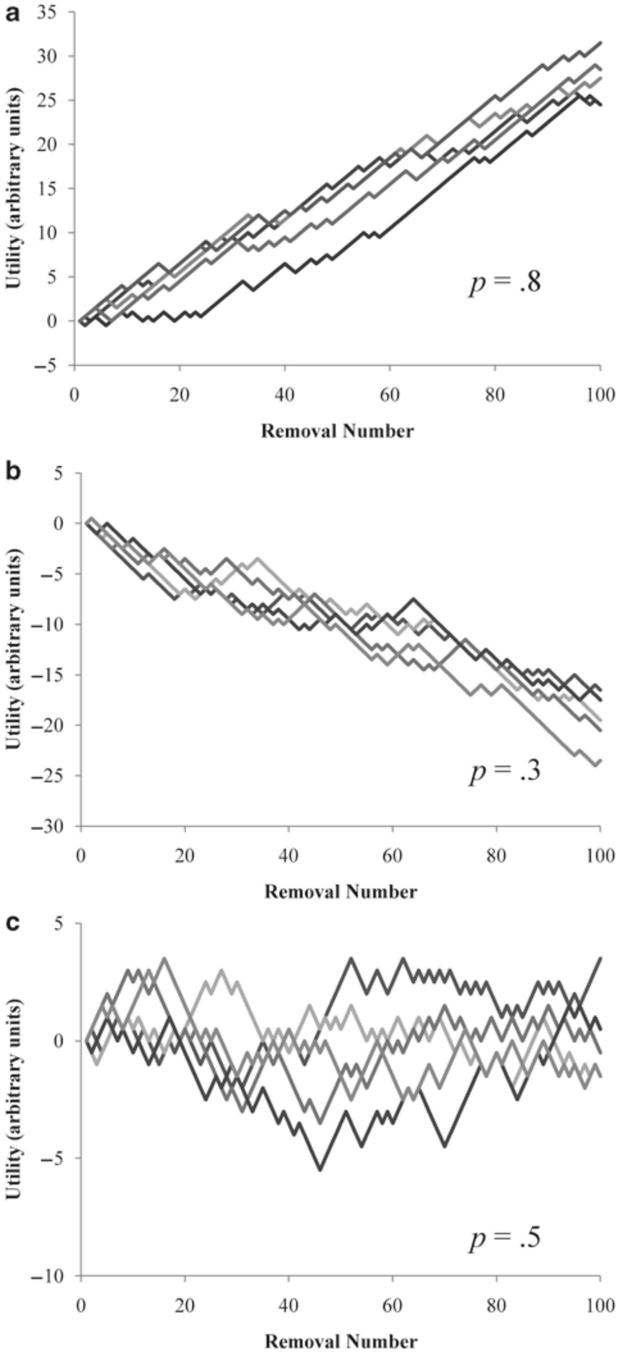

Fig. 8.3 Simulated core reduction trajectories for three raw materials with different error probabilities. The trajectories were generated by iterating Eq. 8.2 with an initial value of $x_0=0$ and $\varepsilon=0.5$. (**a**) When raw material quality is high ($p=0.8$), the utility of detached pieces increases away from the initial value. (**b**) When quality is low ($p=0.3$), utility decreases. (**c**) At intermediate raw material quality ($p=0.5$), some trajectories end up above the starting value ($x_{100}>0$), while others end up below the starting value ($x_{100}<0$)

utility of the current detached piece is perceived to be *too low* because there is a high expectation that the next and, perhaps, all subsequent flakes are also likely to have a utility that is *too low*. More technically, I define a boundary utility x_n* such that, for each flake removal n in the reduction process, if the utility of the current product $x_n \geq x_n*$ then core reduction is continued. However, if $x_n < x_n*$ then reduction is terminated and the core is immediately discarded. Values of x_n* plotted against removal number n form a boundary curve for the entire reduction process. The boundary curve describes the conditions under which it is optimal to discard the core rather than to continue with a current reduction trajectory.[1]

There are a number analytically demanding approaches to estimating the features of optimal stopping boundary curves (see also Brantingham 2007; Dixit and Pindyck 1994). I develop a simple technique for approximating the shape and location of the boundary curve based on simulation. By iterating Eq. 8.2, I simulate repeated core reduction trajectories consisting of a maximum of 100 reduction steps; i.e., each simulated core has a maximum use life of 100 removals. Simulated core reduction events are partitioned into those that successfully reach a target utility T, defined a priori, and those that did not. T may be equated with common currencies such as cutting edge length or resharpening potential. Returning to Fig. 8.3 as an example, if one arbitrarily sets a target utility $T=5$, then all the trajectories in Fig. 8.3a would be classified as successful in having reached the target, whereas all the trajectories in Fig. 8.3b would be considered unsuccessful. All the reduction trajectories represented in Fig. 8.3c are also ultimately unsuccessful, though one comes very close to reaching T in the last few reduction steps. Define min[x_n] as the minimum utility observed at each step in the reduction process considered over all of the trajectories that managed to reach the target utility T. Each value of min[x_n] therefore represents the cumulative value of negative errors, through the removal of n, allowable if a reduction trajectory is to reach the target utility within the use life of the core. In other words, min[x_n] is how far the mighty core can fall and still have hope of getting back up. I take min[x_n] to be an approximation of x_n*. In all instances below, free boundaries were constructed prior to collecting data on discard by simulating 10,000 core reduction events. The free boundary is then interpolated using a nonlinear least squares regression of simulated min[x_n] against removal number.

Figure 8.4a provides an example of a boundary curve defined using the procedures detailed above. The starting utility is $x_0=0$, probability of a positive error $p=0.5$, error magnitude $\varepsilon=\pm 0.5$, and a maximum number of reduction steps $N=100$. Figure 8.4b illustrates how the boundary curve "weeds out" reduction trajectories headed away from a desired target utility. Note that the evaluation of x_n against x_n* occurs after each removal in the reduction process and a decision is then made whether to stop or to continue reduction. This procedure is important for two

[1]A boundary curve x_n* is frequently termed as a "free boundary" because the shape and position of the curve cannot be predicted a priori, but rather result from the unfolding of the random process itself. In the case of core reduction, the approximate features of the free boundary might be known *a priori* as a result of previous experience reducing the raw material in question. However, each piece of raw material will still be unique in many features requiring a dynamic adjustment of the boundary to suit the results of an actual sequence of flake removals.

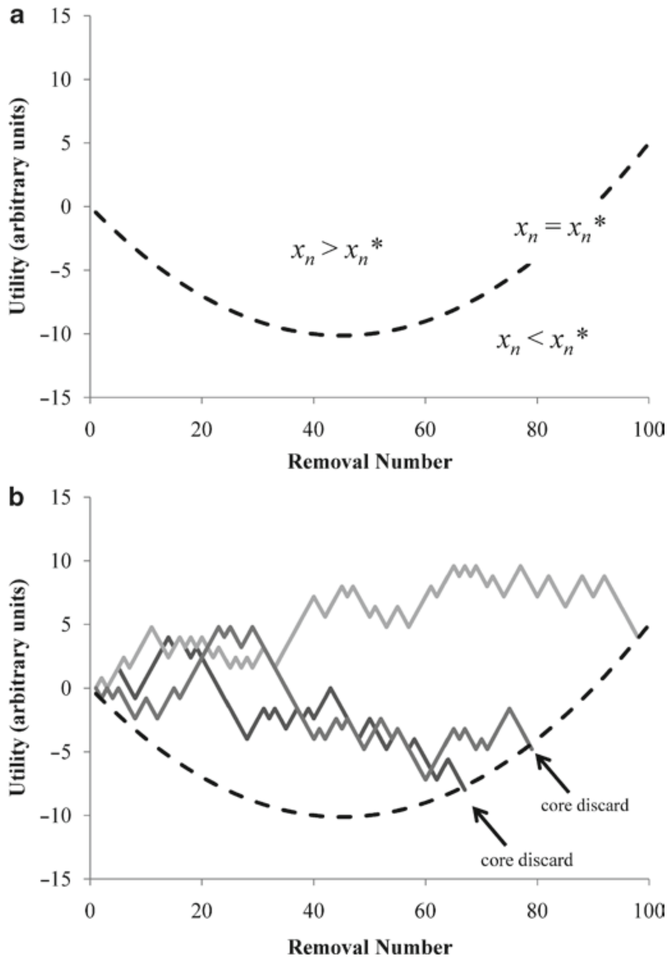

Fig. 8.4 (**a**) A boundary curve divides core reduction into two regions based on whether a trajectory is likely to reach a predetermined utility (e.g., a desired blade length or weight). It is optimal to continue core reduction as long as the utility of a product just removed from a core is greater than the boundary value for that reduction step. (**b**) If the value of a product just removed falls below the boundary value, then the core should be discarded. Simulation parameters: maximum reduction steps $N = 100$; target utility $T = 5$ AU; error size $\varepsilon = 0.5$ AU; and error probability $p = 0.5$

reasons. First, it means that the decision-making process is dynamic in the sense that it is constantly being adjusted to accommodate the results of each flake removal. Second, it provides an effective mechanism for controlling opportunity costs. For example, the first core discard in Fig. 8.4b occurs after observing the utility of removal number 23. Discard at this reduction stage frees up time and energy (equivalent to $N - n = 77$ removals) that may be dedicated to reducing a different core.

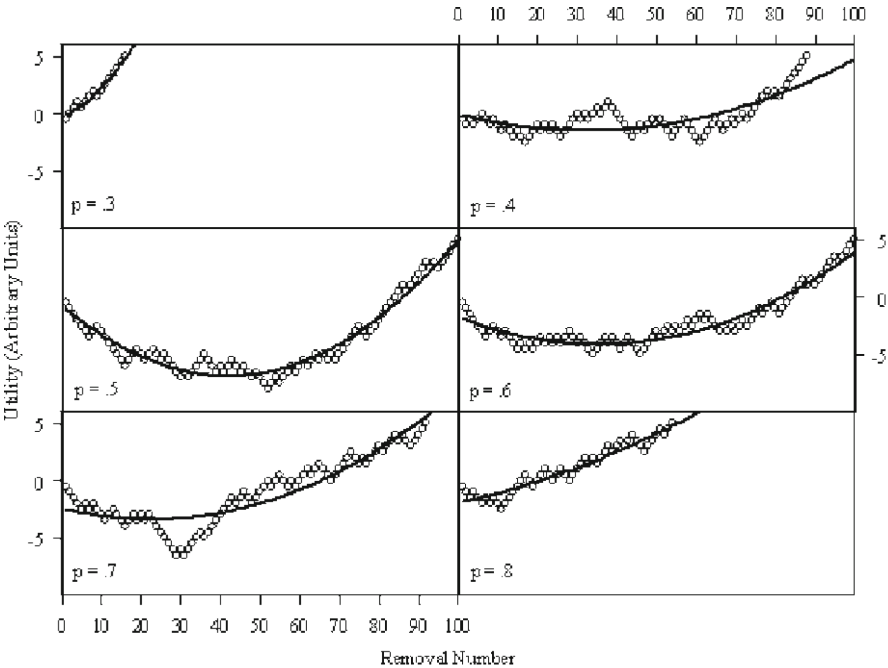

Fig. 8.5 Discard boundary curves (x_n*) for six different values of p. The boundary curves define the optimal points at which to discard a core as a function of the utility of products removed at each stage of reduction (see Fig. 8.4). Boundary curves increase in concavity approaching values of $p=0.5$, but decrease in concavity and increase in slope for values of $p \ll 0.5$ and $p \gg 0.5$. Each boundary curve represents the minimum utilities min[x_n] at each reduction stage n observed among sets of reduction trajectories that hit an arbitrary utility target. Simulation parameters: $x_0=0$ AU; $\varepsilon=0.5$ AU; $N=100$; and $T=5$

The shape of the boundary curve x_n* is dependent upon both the magnitude of reduction errors ε and the probability of encountering a positive error p. Variation in ε alters the concavity of the boundary curve without substantially changing location. Variation in p has a more complex effect and is therefore treated in detail here. Figure 8.5 shows boundary curves computed for core reduction trajectories where the probability of a positive error ranges from $p=0.3$–0.8. When $p=0.3$ (negative errors are approximately 2.3 times more common than positive errors), the boundary curve is very steep and displays positive slopes (Fig. 8.5a). As p approaches 0.5 (negative and positive errors occur with approximately the same frequency), the boundary curve becomes increasingly concave (Fig. 8.5b, c). As p rises above 0.5 (the point where positive errors become more common than negative errors), the boundary curve decreases in concavity and slopes again become more positive (Fig. 8.5d–f).

Despite the superficial similarity between the boundary curves for $p \ll 0.5$ and $p \gg 0.5$, the two boundaries have dramatically different effects on patterns of core

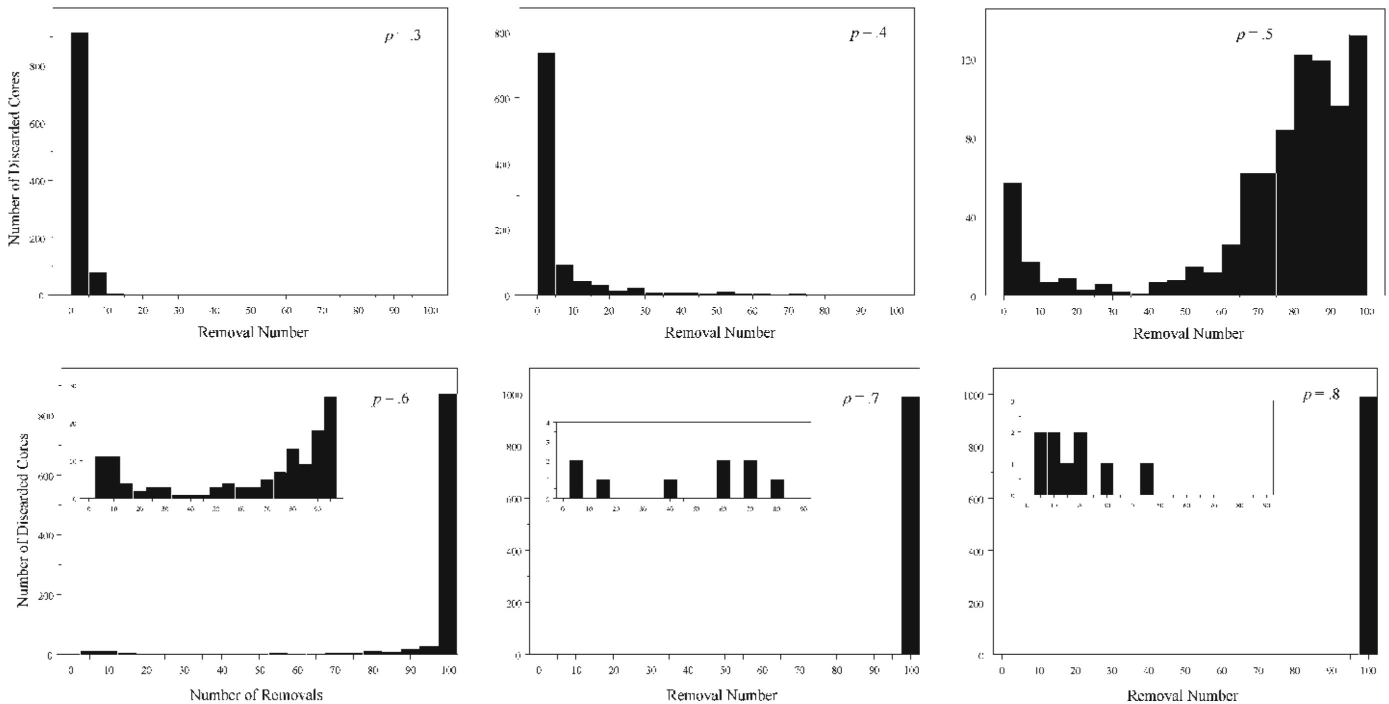

Fig. 8.6 Discard distributions simulated for Markov cores with six different error probabilities. Low-quality materials (p<<0.5) generate core discard distributions with a peak at low-reduction intensities and a right-skew dependent upon the value of p. Intermediate quality materials ($p \sim 0.5$) generate a U-shaped discard distribution with many cores discarded both in early and late stages of reduction, but lower numbers discarded at intermediate reduction intensities. High-quality materials (p>>0.5) show the majority of cores discarded at high-reduction intensities, but a small number of cores are always discarded at early reduction stages if they accumulate negative errors at a fast initial rate. Data represent 1,000 simulated core reduction trajectories for each value of p. Other parameters are held constant: initial utility $x_0 = 0$ AU; error size $\varepsilon = 0.5$ AU; maximum reduction intensity $N = 100$. Cores are discarded at reduction step n if they cross the boundary utility x_n^* or, if they remain above the boundary, at the maximum reduction intensity N. See Fig. 8.4 and text for details. Inset panels show a close-up view of the frequencies of discarded cores at moderate and low-reduction intensities

discard. Using the boundary curves presented in Fig. 8.5, I simulated core reduction and discard following the procedure shown in Fig. 8.4b; core reduction trajectories are generated by iterating Eq. 8.2 and core discard is recorded either when (1) the reduction trajectory contacts the discard boundary or (2) if the maximum number of removals N have been obtained. Figure 8.6 presents frequency distributions of the discard stages (i.e., number of removals n at discard). Each panel tabulates the results for 1,000 simulated reduction trajectories for six different values of p, with $x_0=0$ AU, $\varepsilon=0.5$ AU, and a maximum core use life $N=100$. The shape of the discard distributions is substantially different from that generated by the Bernoulli core model (compare to Fig. 8.1a).

First, note that none of the discard distributions are normal (Gaussian) in shape. Rather, core discard patterns are right skewed for values of $p \ll 0.5$, with the strength of the skew increasing as p increases. In other words, as p (i.e., raw material quality) increases toward 0.5, there is an increasing tendency for cores to be reduced farther, though the majority of cores are still discarded almost immediately after reduction begins. The reason for the peak in discard at very low-reduction intensities is that boundary curves for low p effectively track the rate at which positive errors accumulate. If positive errors do not accumulate fast enough (a rate greater than or at least proportional to the slope of x_n*) then a core is discarded. At low p, this condition is very strict (i.e., slope of x_n* is large and positive).

As p approaches 0.5, the discard distribution takes on a strong U-shape, with large numbers of cores being discarded both at low- and high-reduction intensities and an even representation of cores at intermediate reduction intensities. The peak in core discards at low-reduction intensities represents the boundary curve "weeding out" those cores that accumulate negative errors too quickly as reduction begins – the negative error accumulation rate exceeds the slope of x_n*. In contrast, the peak in core discards at high-reduction intensities represents "weeding out" based on an insufficient positive error accumulation rate. The intermediate region defined by relatively low, but even core discard reflects a tolerance for the accumulation of some negative errors over the course of core reduction. Most of the correction of these errors is accomplished either early or late in reduction, but not in between.

Contrary to what might be expected given the simulated discard patterns for $p \ll 0.5$, the distribution of core discard for $p \gg 0.5$ is not left skewed. As p increases above 0.5, core discards increasingly concentrate in two zones, a very large peak at high-reduction intensities and a small peak at low-reduction intensities. The distribution looses all traces of core discards at intermediate reduction intensities.

Evaluating the Markov Core Model

The Markov core model is perhaps best suited to describing core technologies that exploit the relationship between the morphology of flake scars to predetermine the size and shape of subsequent removals. Levallois technologies are the earliest and best-known

core technologies to make use of such relationships. In particular, Van Peer (1992) has shown using extensive refits that the microtopography of flake scar ridges correspond to the shapes of Levallois products removed from cores. In the case of centripetal Levallois technology, ridges from more than one previous flake removal play a role in determining the size and shape of a single Levallois product. The Markov model as presented above may be a bit of a stretch in this case. However, the assumptions of the Markov core model seem more appropriate for Levallois blade technologies, where each blade removed establishes a linear ridge which serves as a template for the next blade.

Shuidonggou, an early Upper Paleolithic site in Northwest China dating to ca. 25 ka, is dominated by Levallois blade technology based predominantly on alluvial cobbles of silicified limestone (Brantingham et al. 2001). Since the Markov core models make predictions about the distribution of reduction intensity across cores, it is necessary to derive such a measure for the Levallois blade cores recovered from Shuidonggou. Here, I use core remnant use life, which is an estimate of the number of blades that could have been removed from a core if it had not been discarded. Remnant use life is calculated as the core thickness minus the expected thickness of the "slug" of unusable material remaining when a core is completely spent. The typical "slug" at Shuidonggou is 20 mm thick (Brantingham 1999). The usable material in a discarded core is then divided by the average Levallois blade thickness observed in the assemblage. At Shuidonggou, the average thickness of Levallois blades is 7.6 mm. Remnant use life is a measure of the number of additional blades that could have been removed from a core had it not been discarded. The results are presented in Fig. 8.7 for unidirectional and bidirectional Levallois blade cores.

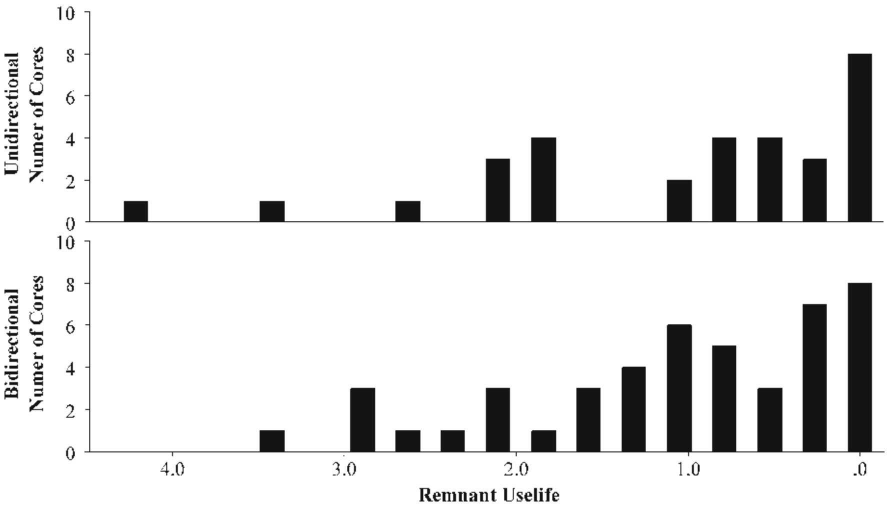

Fig. 8.7 Remnant use life measured for unidirectional and bidirectional blade cores from the Shuidonggou early Upper Paleolithic site, China. Remnant use life is an estimate of the number of blades that could potentially be removed from a discarded core. It is calculated as the discarded core thickness minus the average thickness of the "slug" of unusable raw material in a spent core (~20 mm). The resulting value is then divided by the average thickness of blades seen at the site (~7.6 mm)

Reduction intensity of Levallois cores at Shuidonggou meets some of the expectations of the Markov core model. In particular, the distribution of remnant use life is positively skewed with an increasing number of cores reduced close to the maximum (Fig. 8.7). In comparison with the simulations presented in Fig. 8.6, reduction of silicified limestone appears to be similar in some ways to an error process with $p \gg 0.5$; i.e., silicified limestone is a high-quality raw material which produces many more positive than negative errors during reduction.[2] Remnant use life does not appear to be similar to the "U-shaped" profiles of intermediate quality materials (i.e., $p \sim 0.5$) (but see below), nor the negative skew reduction intensity distributions of low-quality raw materials ($p \ll 0.5$). However, observed remnant use life among discarded Levallois cores at Shuidonggou is unlike the simulated distributions with $p \gg 0.5$ in that it increases gradually. Simulated reduction intensity for $p \ll 0.5$ show many more cores – sometimes an order of magnitude more at the simulated sample sizes – making it all the way through the reduction process.

The observed distribution of remnant use life at Shuidonggou could be most similar to the "U-shaped" profile for intermediate quality materials, but without the branch of the "U" representing cores discarded early in the reduction process. This possibility should not be surprising since Fig. 8.7 considers only cores that can be typologically classified as Levallois blade cores. Many cores that were discarded early in reduction may be nondiagnostic since they have not accumulated enough attributes to be unequivocally assigned to a Levallois reduction strategy. Nevertheless, such nondiagnostic cores may have been started with the intention of producing a Levallois blade core. This may be a safe assumption for nondiagnostic cores in the Shuidonggou assemblage. More than 57% (68 of 119) cores based on silicified limestone are formally classified as Levallois blade cores and 16% (19 of 119) are classified as polyhedral. However, including nondiagnostic silicified limestone cores among the diagnostic Levallois blade cores does not change the overall shape of the remnant use life distribution (Fig. 8.8). Thus, while the Markov core model may offer a reasonably close approximation of the decision-making process involved in Levallois blade core reduction at Shuidonggou, the observed differences with theoretical expectations suggest that a more sophisticated model is probably required.

Price Core Technology

Most lithic specialists would agree that the decision making that takes place during core reduction involves much more than simply deciding when to abandon a core that is proving to be unproductive. Rather, most core reduction strategies combine multiple, distinctive flaking actions that are combined in different proportions to achieve different economic goals. Indeed, it is possible to view the design of core technologies as the assembly of different flaking actions over the use life of the core.

[2] Note that direction of the axes in Figs. 8.7 and 8.8 are reversed so that reduction intensity increases towards the right.

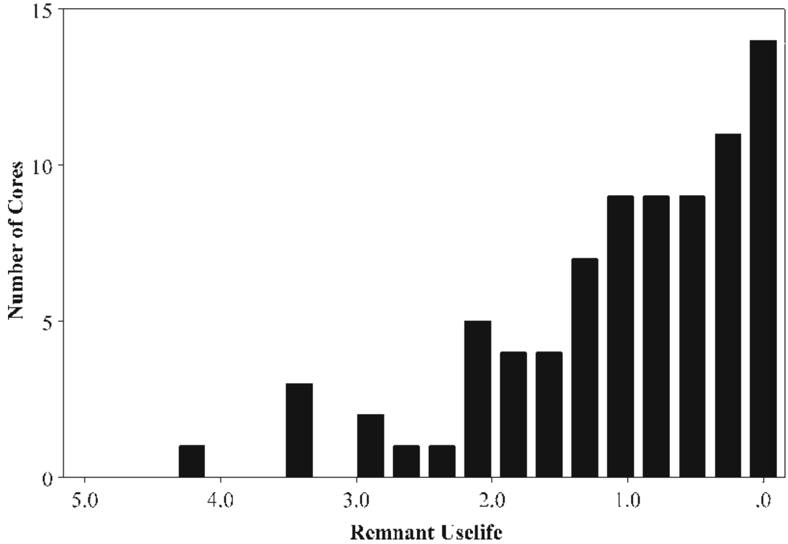

Fig. 8.8 Remnant use life of formal Levallois blade cores and nondiagnostic cores based on silicified limestone from Shuidonggou

It is possible to model this more complicated situation by attributing to the knapper the ability to weigh the results from different, unique flaking actions, and adjust the proportions at which those flaking actions are deployed at the next reduction step. Consider a collection of different possible flaking actions that we label $i=1, 2, \ldots I$. Each flaking action might be distinctive because of the type of percussor used, magnitude of force applied, angle of impact, location on the core, and so on. Each flaking action i produces k_{in} flakes at reduction step n and a total number of $K_n = \sum k_{in}$ flakes are produced by all the flaking actions at the reduction step. Let $p_{in} = k_{in}/K_n$ be the proportion of flakes produced by the flaking action i at reduction step n and define x_{in} as the utility of the flakes produced by action i at step n. The mean utility of all flakes produced at reduction step n is then $x_n = \sum p_{in} x_{in}$.

Given these model elements, changes in a core reduction strategy might originate in two ways. First the utility of flakes produced by each strategy might change as a result of an error process like that defined for Markov core technologies.

$$x_{in+1} = x_{in} + \delta_{in}. \quad (8.4)$$

Here, the utility of flakes produce by action i at reduction step $n+1$ is determined by the utility of flakes at step n and some random error δ_{in} drawn from a probability distribution. Unlike the Markov core model presented above, I will assume here that δ_{in} is drawn from a normal distribution with some mean μ and standard deviation σ (see Brantingham 2007). If $\mu > 0$, then errors will tend to be positive more often than negative and will lead the utility of flakes x_{in} to increase. If $\mu < 0$, then errors will tend to be negative and x_{in} will decrease. The sign of μ may be interpreted

as a measure of raw material quality and σ as a measure of the inherent variability in quality of a raw material package.

Second, change may be accomplished by altering the proportions of different flaking actions used at each reduction step. Let w_{in}/w_n be the relative payoff a knapper associates with the flakes produced by action i. Note that relative payoff is the absolute payoff w_{in} divided by the mean payoff over all flaking strategies $w_n = \sum p_{in} w_{in}$. For the sake of simplicity, w_{in}/w_n is taken to be a positive linear function of utilities x_{in}

$$\frac{w_{in}}{w_n} = \frac{\alpha}{w_n} x_{in} + \frac{\beta}{w_n} \tag{8.5}$$

meaning that as the utility of flakes associated with action i increases so does the relative payoff assigned to action i by the knapper. Thus, the proportion of flakes produced by flaking action i in the next reduction step changes as

$$p_{in+1} = p_{in} \frac{w_{in}}{w_n}. \tag{8.6}$$

Since the function describing the relative payoffs associated with different flake utilities is positive, those flaking actions that yield higher relative payoffs (i.e., $w_{in}/w_n > 1$) will come to occupy a dominant proportion of the core reduction strategy. Those flaking actions yielding flakes with lower relative payoffs (i.e., $w_{in}/w_n < 1$) will become proportionally rare in the reduction strategy.

It is possible to combine Eqs. 8.5 and 8.6 to yield a classic replicator equation describing both stochastic sources of change from raw material quality and deterministic sources of change from decisions implemented by the knapper

$$p_{in+1} x_{in+1} = p_{in} \frac{w_{in}}{w_n} \left(x_{in} + \delta_{in} \right). \tag{8.7}$$

Equation 8.7 describes the proportion of the core reduction strategy and the utility associated with flakes produced by flaking action i in the next reduction step $n+1$ given both selection among flaking actions by the knapper *and* stochastic effects of the raw material. Note that there is one such equation for each unique flaking action deployed within a core reduction strategy and that each equation is tied together by the relative payoffs attributed to each flaking action. Figure 8.9 shows the change in the fractional utility for flakes produced by ten different flaking actions over the course of reduction of a single core. Each of the ten flaking strategies initially comprises $p_{in} = 0.1$ of the total core reduction strategy and the fractional utility of each strategy is $p_{in} x_{in} = 10$. The mean utility of the core at the start of reduction is $x_n = \sum p_{in} x_{in} = 100$ (see below). After about 15 removals, the simulated knapper begins to select for those flaking actions that produce higher payoffs and select against those that do not. Seven of the ten initial flaking strategies are no longer deployed by around reduction step 30 and the core reduction strategy consists of three dominant flaking actions. These fluctuate in prominence over the remainder of reduction; action 5 dominates between steps 32 and 69, action 2 between steps 70 and 87, and action 1 between

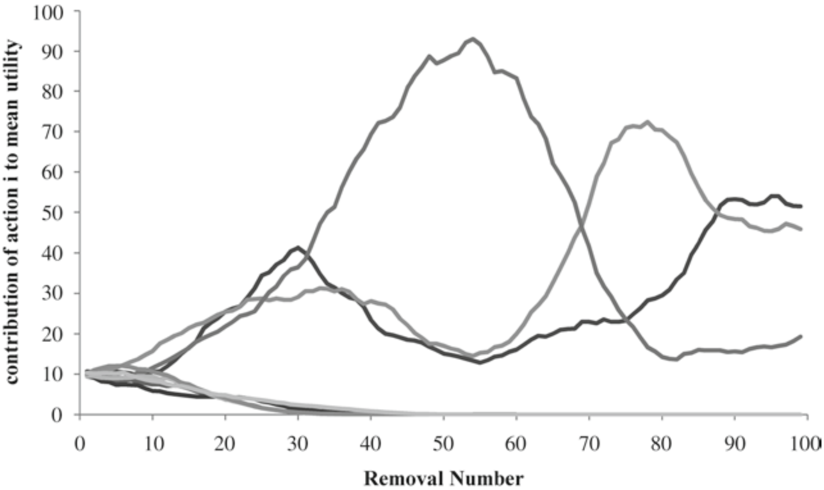

Fig. 8.9 Simulated fractional utilities of flakes produced by ten unique flaking actions in the reduction of one core. Fractional utilities are the proportion of the total strategy made up by action i multiplied by the utility of the flakes from action i at each reduction step (i.e., $p_{in}x_{in}$). The payoff function used in simulated core reduction is $w_{in} = 0.5x_{in} + 1$ (both sides divided by mean payoffs w) and the error process for δ is a normal distribution with mean $\mu = 0$ and standard deviation $\sigma = 1$

step 88 and the discard of the spent core at step 100. The dynamic shifting of different flaking action over the course of the reduction of a single core is at least qualitatively like what is seen for real core technologies (Baumler 1995; Volkman 1983).

However, it is clear that it would be cumbersome to track the trajectory of each flaking actions, even if they were deployed in modest numbers. Moreover, it is debatable whether the decision to discard a core is based on the results of flakes produced by individual flaking actions, independent of the others. Some aggregate measure of core productivity is perhaps more appropriate. Fortunately, we can draw on a very important result from the mathematics of selective processes to describe the evolution of the reduction process in terms of the rate of change in the mean utility of the core (see Brantingham 2007; Frank 1997; Price 1970; Rice 2004).

$$\Delta x = \mathrm{COV}\left[\frac{w_{in}}{w_n}, x_{in}\right] + E\left[\delta_{in}\right]. \tag{8.8}$$

Equation 8.8 is the Price equation (Price 1970) and, in homage, I call the modeled core technology a Price core. Equation 8.8 is derived directly from Eq. 8.7. It partitions the rate of change in the mean utility of a core into: (1) a covariance component describing how the knapper weighs relative payoffs associated with flakes produced by each flaking action and (2) the expected effects of errors (i.e., raw material quality).

There is a vast number of ways in which we could model a Price core technology by parameterizing different payoff functions (Eq. 8.5) and probability distributions describing the character of errors produced during core reduction. This is clearly

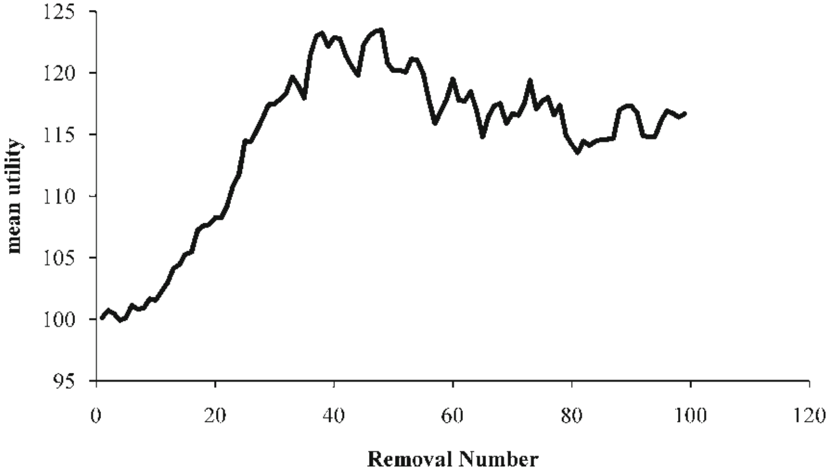

Fig. 8.10 Simulated mean utility of flakes produced in the reduction of one Price core

beyond the scope of this chapter. A quick look at the dynamics of Eq. 8.8, however, suggests that if the sum of the covariance term and the expectation term is positive, then the mean utility of the core will increase regardless of specific parameterizations of the model. An increasing mean utility can happen if both terms of Eq. 8.8 are positive, meaning that both the knapper's ability to select among different flaking actions and raw material quality tend to enhance the utility of flaking products. Mean utility will also increase if one term is positive and the other is negative, but the positive term is much larger. In other words, a very skilled knapper can adjust flaking actions to overcome poor raw materials (i.e., $\mathrm{COV} \gg 0$ and $E < 0$), or a good raw material can make even a mediocre knapper look great (i.e., $\mathrm{COV} < 0$ and $E \gg 0$). Figure 8.10 shows how the selection among the different flaking actions in the case of the simulated core in Fig. 8.9 leads to an increase in mean utility of the flaking products. Here $E[\delta] = \mu = 0$ and all the directionality in the mean utility is the result of a positive covariance between payoffs w_{in}/w_n and utilities x_{in}.

Evaluating the Price Core Model

The last point above suggests that a knapper may be able to select among different flaking actions to steer a core clear of the free boundary which, in the case of the Markov cores described earlier, might be used to decide when to discard a core. Figure 8.11 shows this to be the case for 500 simulated cores where the criterion for core discard is similar to that for Markov cores, namely when the mean utility removed products from a core x_n at reduction step n falls below a mean free boundary x_n*. The simulated Price cores in Fig. 8.11 have payoff function shown with slope $\alpha/w_n = 2$ (Eq. 8.5), mean error distribution is $\mu = 0$ and standard deviation is $\sigma = 2$. Interestingly, the raw material quality as modeled here is based on a normal

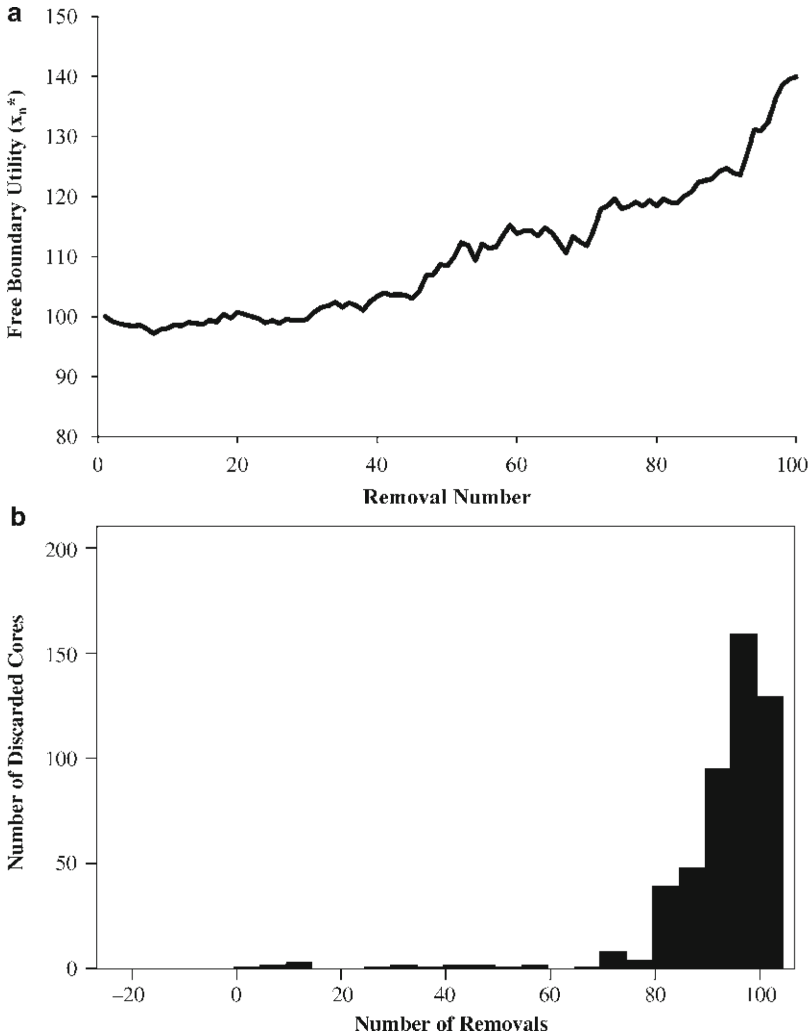

Fig. 8.11 The simulated free boundary (*top*) for Price cores where there is a slight positive payoff function allowing knappers to selecting between different flaking strategies and an error distribution with a mean of zero and a standard deviation of two (moderate quality raw material). The discard distribution for simulated cores (*bottom*) shows a gradual increase in the number of discarded cores as one approaches the end of the use life of each core. The simulated distribution is qualitatively similar to that seen for Levallois blade cores at Shuidonggou

distribution with a mean of zero is conceptually similar to the Markov core example with the probability of a positive error $p=0.5$; i.e., positive and negative errors occur with approximately equal frequency. However, the free boundary in the case of the Price core modeled here is much more similar to that for a raw material of much higher quality (see Fig. 8.5 where $p=0.7$). This provides casual confirmation that the ability to select between different flaking actions can outweigh the effects

of raw material quality. However, the impact on core discard distributions is not directly comparable. Here, we see a single-tailed distribution with the number of discarded cores increasing gradually as the maximum core use life is approached. In contrast, for the Markov cores modeled above, any value of $p > 0.5$ shows most cores being discarded at maximum use life. The resemblance between the simulated discard distribution for Price cores and the remnant use life distributions for Levallois blade cores from Shuidonggou is striking (see Figs. 8.7 and 8.8). While this does not necessarily confirm that Levallois blade technology at Shuidonggou follows a Price core reduction strategy, it does suggest that further modeling work is warranted.

Conclusions

The goal of this chapter is to develop a series of formal mathematical and simulation models to account for the variability in the intensity of reduction observed across different stone core technologies. Three models were presented each of which made increasingly complex assumptions about the decision-making process deployed during the course of reducing a mass of raw material. The models may be thought of in an evolutionary light, though no implications about long-term patterns of stone technological change were derived. The three models were compared with data on core reduction intensity from Olduvai Gorge and Shuidonggou, an early Upper Paleolithic site in Northwest China dating to approximately 25 ka.

Bernoulli core technology was developed as a model of reduction where the utility of flakes produced is binary (i.e., good or bad), the probability of obtaining a good flake is fixed by stone raw material quality, and each flake removal is independent of all other flake removals. Bernoulli core reduction proceeds until the knapper obtains some predetermined number of good flakes, and the prediction is that poor quality raw materials will be reduced much more intensively than high-quality raw materials because it takes much longer to produce the desired number of good flakes. This prediction is contrary to the general assumption made by lithic technologists. Comparison with data on weight-standardized flake scar counts for several sites from Olduvai Gorge suggests that Oldowan core technology is not a Bernoulli core technology. In particular, it is possible to reject the hypothesis that poor quality raw materials are more intensively reduced. Rather, the opposite reduction pattern appears to hold–higher-quality materials are more intensively reduced–suggesting that Olduvai hominins were making decisions to discard cores that were not proving to be economically productive. This level of decision making is consistent with recent evidence of very selective raw material use (Stout et al. 2005) and evidence for surprisingly sophisticated approaches to core reduction (Delagnes and Roche 2005).

Markov core technology is a model that accounts for decisions to discarded cores before they have reached some predetermined target utility. The Markov core model also posits flakes produced in a sequence are not statistically independent of one another, but rather the utility of a flake just removed from a core is partially

determined by the utility of the preceding flake along with some error that arises from the quality of the raw material being reduced. This assumption leads to a dynamic model where the utilities of flakes removed from a core perform a random walk. If we define some threshold utility that the knapper is trying to achieve through core reduction, then it is possible to learn about reduction trajectories that do not reach this threshold and set up a set of criteria that would cue the knapper that a given core was not likely to reach the desired threshold utility. In technical terms, the set of cues used to decide that a core is not likely to reach a threshold utility is called a free boundary. Simulation suggest that core reduction that incorporates an autocorrelation of flake utilities and allows for core discard if the utility of a flake falls below the free boundary lead to very distinctive core discard patterns. In particular, for intermediate quality raw materials where positive and negative errors are equally likely to occur, the frequency of cores discarded at different reduction intensities should be "U-shaped" – many cores minimally reduced, few cores at intermediate reduction intensities and many cores that are intensively reduced. If negative reduction errors are more common than positive errors, then most cores are discarded very early during reduction. The opposite is true for materials that produce more positive errors than negative. Here, most cores are reduced to a complete spent state. Comparisons of expectations with data on remnant use life among Levallois blade cores from the early Upper Paleolithic site of Shuidonggou, Northwest China, suggest that the Markov core model is closer to the mark. However, the discard pattern at Shuidonggou suggests a gradual increase in the probability that a core is discarded as one approaches the maximum reduction intensity.

The model of Price core technology builds on the Markov model in adding into the system the possibility that core reduction strategies are mixtures of several independent types of flaking actions, and allowing the knapper to selectively deploy these flaking actions depending upon the utility of the flakes each produces. Raw material quality also plays an important role here in generating the variability between different flaking actions. The Price core model generates an interesting picture of core reduction as a sequence of dynamic shifts in the importance of different flaking actions over the course of reduction; some actions predominate early, others take over during intermediate stages and still others are common toward the end of the use life of a core. The Price equation – after which this core technology is named – is derived from the different elements discussed above and provides clues about the interaction between the knapper's ability to steer core reduction in different directions and the impact of raw material quality. Indeed, I propose that the Price equation provides an interesting way of conceiving of stone technological design (see also Brantingham 2007):

$$\Delta x = \underbrace{\mathrm{COV}\left[\frac{w_{in}}{w_n}, x_{in}\right]}_{\text{core technological design}} + \underbrace{E\left[\delta_{in}\right]}_{\text{raw material quality}} .$$

Clearly, much more work has to be done to flesh out this suggestion. However, it is encouraging to note that a Price core simulated discard distribution – using as a

criterion to discard the point where the mean utility of flake products crosses a free boundary – resembles much more closely the observed pattern of core remnant use life seen at Shuidonggou than simpler models.

Acknowledgments This work was inspired by Huberman et al. (1998), showing that inspiration can come from anywhere. I am indebted to Yuki Kimura who provided raw data on flake scar counts and core weights from the Olduvai sites she examined in her dissertation. Todd Surovell and Matt Grove kindly provided helpful comments on a previous version.

References

Bamforth, D.B., 2002. High-tech foragers? Folsom and later Paleoindian technology on the Great Plains. *Journal of World Prehistory* 16: 55–98.

Baumler, M.F., 1995. Principles and properties of lithic core reduction: implications for Levallois technology. In *The Definition and Interpretation of Levallois Technology*, edited by H.L. Dibble and O. Bar-Yosef, pp. 11–23. Prehistory, Madison.

Beck, C., Taylor, A.K., Jones, G.T., Fadem, C.M., Cook, C.R. and Millward, S.A., 2002. Rocks are heavy: transport costs and Paleoarchaic quarry behavior in the Great Basin. *Journal of Anthropological Archaeology* 21: 481–507.

Boëda, E., 1995. Levallois: a volumetric construction, methods, a technique. In *The Definition and Interpretation of Levallois Technology*, edited by H.L. Dibble and O. Bar-Yosef, pp. 41–68. Prehistory, Madison.

Brantingham, P.J., 1999. *Astride the Movius Line: Late Pleistocene Lithic Technological Variability in Northeast Asia*, University of Arizona, Unpublished PhD Dissertation.

Brantingham, P.J., 2007. A unified evolutionary model of archaeological style and function based on the Price Equation. *American Antiquity* 42: 395–416.

Brantingham, P.J., Krivoshapkin, A.I., Li J. and Tserendagva, Y., 2001. The initial Upper Paleolithic in Northeast Asia. *Current Anthropology* 42: 735–746.

Brantingham, P.J. and Kuhn, S.L., 2001. Constraints on Levallois core technology: a mathematical model. *Journal of Archaeological Science* 28: 747–761.

Braun, D. R., Tactikos, J.C., Ferraro, J.V., Arnow, S.L. and Harris, J.W.K., 2008. Oldowan reduction sequences: methodological considerations. *Journal of Archaeological Science* 35: 2153–2163.

Delagnes, A. and Roche, H., 2005. Late Pliocene hominid knapping skills: the case of Lokalalei 2C, West Turkana, Kenya. *Journal of Human Evolution* 48: 435–472.

Dibble, H.L., 1995. Middle Paleolithic scraper reduction: background, clarification, and review of the evidence to date. *Journal of Archaeological Method and Theory* 2: 299–368.

Dibble, H.L. and Bar-Yosef, O., 1995. *The Definition and Interpretation of Levallois Technology*. Prehistory Press, Madison.

Dixit, A.K. and Pindyck R.S., 1994. *Investment Under Uncertainty*. Princeton University Press, Princeton, NJ.

Elston, R.G. and Brantingham, P.J., 2003. Microlithic technology in Northeast Asia: a risk minimizing strategy of the Late Paleolithic and Early Holocene. In *Thinking Small: Global Perspectives on Microlithization*, edited by R. G. Elston and S. L. Kuhn, pp. 103–116. Archaeological Papers of the American Anthropological Association, No 12, Washington, DC.

Frank, S.A., 1997. The Price Equation, Fisher's fundamental theorem, kin selection, and causal analysis. *Evolution* 51: 1712–1729.

Huberman, B.A. et al., 1998. Strong regularities in World Wide Web surfing. *Science* 280:95–97.

Kimura, Y., 1999. Tool-using strategies by early hominids at Bed II, Olduvai Gorge, Tanzania. *Journal of Human Evolution* 37: 807–831.

Kimura, Y., 2002. Examining time trends in the Oldowan technology at Beds I and II, Olduvai Gorge. *Journal of Human Evolution* 43: 291–1321.

Kuhn, S.L., 1994. A formal approach to the design and assembly of mobile toolkits. *American Antiquity* 59: 426–442.

Kuhn, S.L., 2004. Evolutionary perspectives on technology and technological change. *World Archaeology* 36: 561–570.

Lycett, S.J., 2008. Acheulean variation and selection: does handaxe symmetry fit neutral expectations? *Journal of Archaeological Science* 35: 2640–2648.

Nelson, M.C., 1991. The study of technological organization. *Archaeological Method and Theory* 3: 57–100.

Pelcin, A.W., 1997. The effect of core surface morphology on flake attributes: evidence from a controlled experiment. *Journal of Archaeological Science* 24: 749–756.

Potts, R., 1991.Why the Oldowan? Plio-Pleistocene tool making and the transport of resources. *Journal of Anthropological Research* 47: 153–176.

Price, G.R., 1970. Selection and covariance. *Nature* 227: 520–521.

Rice, S.H., 2004. *Evolutionary Theory: Mathematical and Conceptual Foundations*. Sinauer, Sunderland, MA.

Stout, D., Quade, J., Semaw, S., Rogers, M.J. and Levin, N.E., 2005. Raw material selectivity of the earliest stone toolmakers at Gona, Afar, Ethiopia. *Journal of Human Evolution* 48: 365–380.

Toth, N.P., 1982. *The Stone Technologies of Early Hominids at Koobi Fora: An Experimental Approach*. Unpublished PhD, University of California, Berkeley.

Van Peer, P., 1992. *The Levallois Reduction Strategy*. Prehistory Press, Madison.

Volkman, P., 1983. Boker Tachtit: core reconstruction. In *Prehistory and Paleoenvironments in the Central Negev, Israel The Avdat/Aqev Area*, edited by A.E. Marks, pp. 127–190. Southern Methodist University Press, Dallas.

Chapter 9
Cultural Transmission, Genetic Models and Palaeolithic Variability: Integrative Analytical Approaches

Stephen J. Lycett

Abstract It is increasingly recognised that cultural transmission involves inheritance, variation of practice and the differential representation of particular variants in subsequent generations due to a variety of sorting mechanisms. As such, patterns of cultural variation and change (including those seen in lithic artefacts) can be seen as an emergent property of a process of "descent with modification." Two immediate analytical implications arise from recognition that changes and variation in lithic artefacts are partly brought about by a process of descent with modification, which have particular relevance for Palaeolithic archaeology. The first of these is that understanding the historical process of lineage descent and diversification (i.e. phylogeny) becomes an imperative research goal; the second is that many of the factors known to structure variation in genetic data (e.g. drift, selection, demography and dispersal) will have an influence upon patterns of variation in the attributes of artefacts. Here, using a data set of Acheulean handaxes, it is demonstrated that methodologies designed to address these issues in biology might profitably be used to address analogous questions pertaining to Palaeolithic technologies.

Change and Variation in Lithic Assemblages as a Process of "Descent with Modification"

In recent years, cultural transmission theory has been applied to a wide array of examples in the study of material culture (Eerkens and Lipo 2007). Such a theory is based on the idea that when people engage in artefact manufacture, they employ – at various stages – a set of socially inherited ideas, skills and knowledge that come to influence the final form of that artefact. Hence, the central concept here is that traditions of artefact manufacture seen in the archaeological record reflect the copying or inheritance of ideas from person-to-person. This key concept of inheritance has led

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its proponents to draw comparisons not only between the process of knowledge inheritance and genetic inheritance (e.g. Neiman 1995; Lipo et al. 1997; Shennan 2000), but also between the process of cultural change evident through time in the archaeological record and that of organismal change seen in the fossil record (e.g. Clarke 1968; O'Brien and Lyman 2000; Kuhn 2004; Mesoudi et al. 2006). Central to such a comparison is Darwin's (1859: 459) concept of "descent with modification."

As Darwin outlined, descent with modification is a process that involves inheritance, variation and sorting. Whenever these three phenomena occur together, evolution (i.e. "descent with modification") *must* occur. Note that there is no necessary stipulation regarding how transmission must take place (e.g. via genetic means versus social means)[1] nor a stipulation regarding specific sources of variation (e.g. genetic mutation versus copying a skill imperfectly, or even deliberately choosing to embellish it). Likewise, several means of sorting may influence whether particular variants are passed to subsequent generations in lesser or greater numbers, both in the biological world and in culture. Such mechanisms include – but are not necessarily limited to – artificial selection, natural selection and even stochastic forces (e.g. drift). A further factor to bear in mind is that although genetic inheritance occurs strictly between parents and progeny, the non-kin avenues of inheritance that may occur in the replication of socially transmitted traditions are not excluded when evolution is defined in these terms (a constant source of confusion that arises when talking of cultural evolution that bears emphasising). Indeed, the appropriateness of comparison between biological descent with modification and cultural descent with modification was not lost on Darwin himself, who compared the process of language change to that of change in the natural world when first describing this mechanism (1859: 422).

Lithic artefacts show variety in form within and between assemblages, the source of which has formed a focus of discussion for many decades (e.g. Bordes 1961; Mellars 1970; Binford 1973; Dibble 1987). Yet, the combination of visible repetition in specific knapping routines in the archaeological record over time, combined with ethnographic data concerning the learning of stone artefact manufacture in traditional societies, ensures that social inheritance cannot be ignored as a major vector of influence in forming the available record (Clarke 1968; Mithen 1996, 1999; Shennan and Steele 1999; Stout 2002, 2005; Tostevin 2003; Kuhn 2004). It is perhaps unsurprising, therefore, that in recent years, cultural transmission theory has been applied to lithic artefacts to examine a series of issues (see Shott 2008 for review). Of course, ideas and traditions of artefact manufacture interact with the material world, which may also influence the final form of an artefact (e.g. raw material). Hence, just as the genotype is merely a blueprint for the biological phenotype, the latter of which may be influenced by a variety of environmental factors during growth and development, so the artefact may find itself subject to environmental influences that affect form beyond that of the ideas and skill traditions possessed by its manufacturer. However, as will be shown below, using cultural transmission theory as a basis allows questions concerning these potential forces to be situated in an empirically testable framework.

[1]It is worth reflecting that Darwin himself knew nothing of genes and the specifics of what later became known as the principles of Mendelian inheritance.

Recent lithic case studies have considered a diversity of issues including the evolution and diversification of specific traditions (e.g. O'Brien et al. 2001; Darwent and O'Brien 2006; Buchanan and Collard 2008; Lyman et al. 2009), colonisation processes in the Americas (e.g. Buchanan and Collard 2007), processes of selection (Lyman et al. 2008), modes of transmission (e.g. Bettinger and Eerkens 1999; Mesoudi and O'Brien 2008a, b; Hamilton and Buchanan 2009) and the effects of natural catastrophes on artefactual variation (Riede 2008). Such a burgeoning literature would appear to attest to the utility of cultural transmission theory as it applies to lithic artefacts. However, despite the recent rise in the application of cultural transmission theory (and associated techniques of analysis) to lithic artefacts, the majority of case studies to date have been conducted on Holocene artefacts made by *Homo sapiens* from the Late Palaeolithic/Mesolithic periods. Only a handful of such studies have applied these same principles to frame formal analyses of artefactual evolution and variation using data from the Lower and Middle Palaeolithic (Vaughan 2001; Lycett 2007b, 2008, 2009a, b; Lycett and von Cramon-Taubadel 2008; Lycett and Gowlett 2008). Such a state of affairs is perhaps even more striking given the growing evidence from both captive and wild chimpanzee populations, which demonstrates that our closest living primate relatives create traditions of behaviour (including technological traditions) via means of social transmission (Whiten 2005; Whiten et al. 1999, 2001, 2005, 2007; McGrew 2004; Biro et al. 2006; Horner et al. 2006; Bonnie et al. 2007; Hopper et al. 2007; Lycett et al. 2007, 2009). Given this evidence, there is no immediate operational reason why the cultural transmission framework of analysis cannot be extended to extinct hominin populations under a unified analytical framework.

Two immediate analytical implications arise from recognition that changes and variation in lithic artefacts are partly brought about by a process of descent with modification, which have particular relevance for Palaeolithic archaeology. Firstly, that phylogenetic methods drawn from biology may be used to understand the evolution and diversification of artefact lineages (Foley 1987; O'Brien and Lyman 2000, 2003a; Kuhn 2004; O'Brien et al. 2008). Secondly, that methods and principles drawn from population genetics can provide a fruitful means of testing hypotheses concerning issues such as drift, technological selection and hominin dispersal (Neiman; 1995; Shennan 2000, 2001; Bentley et al. 2004, 2007; Lycett and von Cramon-Taubadel 2008). The following sections of this paper discuss both the use of phylogenetic methods and population genetics principles, as they might be applied to data from these earlier periods.

Phylogeny and Palaeolithic Variability

Phylogenetics: The Study of Historical Diversification and Descent

Darwin's theory of descent with modification transformed Linnaean taxonomy from a mere hierarchical classificatory scheme of intransmutable taxa into an organisational principle for patterns caused by evolutionary change (Mayr 1982; O'Brien and Lyman 2000).

Hence, wherever there is a process of evolution, an understanding of the relationships (i.e. pattern of diversification and descent) between evolving units becomes an essential goal. Under this framework, phylogenetic analysis is a means of organising groups of things (be they species, populations or artefactual assemblages) into a hierarchical pattern that reflects closeness of genealogical relationship based on the attributes (e.g. genes or morphology) exhibited by individuals within those groups (McLennan and Brooks 2001; O'Brien and Lyman 2003a). It is important to emphasise that in a phylogenetic sense, "relationship" refers explicitly to genealogical affinities rather than mere closeness of similarity (e.g. typological resemblance). In essence, phylogenetics is an historical approach to a given data set (Smith 1994; O'Brien and Lyman 2003a; Lipo et al. 2006; O'Brien et al. 2008).

Recognition that many changes in the artefactual record can be seen as resulting from an historical process of descent with modification mediated by social transmission, has led several recent workers to suggest that phylogenetic methods drawn from biology might yield great potential in the case of archaeological data (Foley 1987; Collard and Shennan 2000; O'Brien et al. 2001). In the case of biology, cladistics has been a commonly used method of phylogenetic reconstruction over recent decades (Eldredge and Cracraft 1980; Quicke 1993; Smith 1994; Kitching et al. 1998; Page and Holmes 1998; Gee 2000; McLennan and Brooks 2001). Subsequently, cladistics has also been adopted by many archaeologists and anthropologists in order to investigate historical questions of phylogeny pertaining to archaeological artefacts and other cultural data (e.g. Collard and Shennan 2000; O'Brien et al. 2001; Tehrani and Collard 2002, 2009; Jordan and Shennan 2003; Darwent and O'Brien 2006; Harmon et al. 2006; Jordan and Mace 2006; Buchanan and Collard 2007, 2008; Lycett 2007b, 2009a, b; Lycett et al. 2007).

As is widely known, cladistics emphasises the importance of using uniquely shared (i.e. "shared-derived") characteristics, rather than shared primitive ("symplesiomorphies") or convergences (i.e. "homoplasies") in determining the phylogenetic relationships between evolved units, while at the same time using the principle of parsimony as a means of choosing between hypotheses of phylogeny when faced with several possible alternatives (Sober 1983). Cladistics can be computationally demanding and is also notorious for its association with esoteric terminology. Fortunately, in recent years, several accessible introductions to the principles and terminology of cladistics have become available (e.g. Kitching et al. 1998; McLennan and Brooks 2001), including some written specifically for archaeologists (O'Brien and Lyman 2003a). It has also been noted that despite the use of rather complex computer algorithms to determine the most parsimonious cladograms, cladistics can conceptually be broken down into a small series of fundamental methodological steps (McLennan and Brooks 2001; Buchanan and Collard 2007).

The first step in any cladistic analysis is to delineate the taxonomic units (i.e. identify those units that one wishes to understand the structure of relationships between). These analytical units are referred to as "Operational Taxonomic Units" (OTUs), and in biology might be individuals, species or populations, while in archaeology might be artefacts or assemblages. The second stage is to generate a character state matrix describing the character states for each OTU. Next, the direction

of evolutionary change ("character polarity" in cladistic terminology) is determined, most commonly via comparison with an outgroup. Thereafter, a branching diagram (i.e. cladogram) is constructed that describes the relationships between OTUs for each character. Finally, in accordance with the principle of parsimony, an ensemble cladogram is constructed that is consistent with the largest number of character trees and also, therefore, requires the least number of ad hoc (non-parsimonious) character state changes to be invoked in order to explain the phylogenetic relationships between the different OTUs. This use of parsimony also explains why cladograms are frequently referred to as Maximum Parsimony (MP) trees.

Testing the Utility of Phylogenetic Methods for Palaeolithic Data: A Case Study Using Acheulean Handaxes

Handaxes are defined by the imposition of a long axis on artefact form by means of invasive bifacial knapping around the edge of a core, nodule or large flake blank (Roe 1976; Isaac 1977; Gowlett 2006). Currently, classic Acheulean handaxes of teardrop, triangular or ovate shape are known from sites across Africa, western Asia, Western Europe, and the Indian subcontinent. Such artefacts date from *ca*. 1.7 MYA (in Africa) to less than 200 KYA (Asfaw et al. 1992; Schick and Toth 1993; Clark 1994; Klein 2005). Acheulean handaxes are truly multidimensional in variation of form, shape and symmetry across their large time-span and geographic distribution (Wynn and Tierson 1990; Clark 1994; Vaughan 2001; Gowlett 2006; Lycett and Gowlett 2008; Lycett and Norton 2010). Hence, they seem an appropriate phenomenon to discuss some of the challenges and potential of phylogenetic approaches to Palaeolithic data.

The idea that phylogenetic methods might usefully be applied to Palaeolithic data of this nature has not been without criticism. One such criticism concerns recognition that stone artefacts can be subject to technological convergence (e.g. McBrearty 2003; Otte 2003). However, convergence is also common in biological data, and as one recent case study has demonstrated (Lycett 2009a), hypotheses of convergence are themselves phylogenetic scenarios that – ironically – can only be evaluated formally with phylogenetic methods. A somewhat related idea is the long-held view that much of stone artefact variation is the product of raw material properties (Goodman 1944), and as such potentially swamp any cultural information that might be present. Fortunately, as will be shown below, the degree to which a cladogram of hypothesised stone artefact relationships is influenced by raw material is a factor that may be determined empirically.

A further challenge concerns the relationship between stone artefact form and socially inherited knowledge. At a proximate level, it is not the attributes of artefacts that are themselves transmitted between individuals. Rather, it is the ideas, concepts, skills and actions surrounding the process of manufacture. However, such entities are not directly amenable empirically in the case of archaeological data; all we are left with is the material (artefactual) products of their implementation and application.

This is closely analogous to the situation that palaeontologists routinely find themselves in when attempting to determine the phylogenetic relationships of extinct taxa from fossils. It is genes that are inherited at the proximate level, yet only morphological attributes are available for study, which must be used as a proxy for the genetically transmitted information.

A further potential problem might therefore be a relative paucity of “cultural” information in stone artefacts of Lower and Middle Palaeolithic age. It might, for instance, be suggested that stone is not as “plastic” as the pottery decorations or carpet designs used in cladistic analyses of later artefacts, and thus does not convey cultural information of the type required to give a reasonable phylogenetic signal. Theoretically, some argument can be made against such a line of reasoning from the outset, and it may even be founded on misconceived ideas that for a phylogenetic model to operate stone knappers must have had some preconceived “mental template” and/or been consciously signalling cultural identity. Fortunately, neither of these assumptions is a necessary requirement of phylogenetic approaches to Palaeolithic data. It has long been considered (e.g. Oakley 1958) that certain “traditions” of artefact manufacture result from inherited knowledge about how specific techniques will lead to certain outcomes. However, any culturally transmitted idea or technique surrounding stone tool manufacture – from abrading a platform in a certain type of way with a certain type of abrader, to holding the artefact and/or turning it certain ways during manufacture – may, in principle, result in quantifiable differences in certain attributes of the final product, *whether the knapper is consciously aware of those outcomes or otherwise* (see also Clarkson, this volume). Numerous attributes of manufacture, however subtle, might be applied at the numerous stages of manufacture and result in some unforeseen but quantifiable variable. A corollary of this, is that it is difficult a priori to determine precisely what attributes might be more or less phylogenetically informative in the case of stone tools. Again, it is interesting to note that in palaeontology, systematic morphometric approaches to character acquisition, which explicitly take account of the fact that populations vary in a continuous manner both within and among themselves in terms of their attributes, are increasingly being used in phylogenetic studies (e.g. Adrain et al. 2001). More importantly, as will be shown below, the degree of phylogenetic signal in a resultant tree and the goodness-of-fit to a tree model can be evaluated empirically, once a phylogenetic tree has been constructed.

To investigate these issues in regard to the phylogenetic analysis of Palaeolithic data, a series of analyses were conducted on a data set of Acheulean handaxe assemblages from a series of localities across Europe, Africa, the Near East and the Indian subcontinent (Table 9.1). Quantitative data for a total of 72 characters were collected for each of the ten OTUs (total $n = 255$ handaxes). Information concerning these characters has previously been described in detail elsewhere (e.g. Lycett et al. 2006; Lycett 2007a, b, 2008). However, in brief, the characters comprise a series of data describing overall form (i.e. Characters 1–57), as well as wider attributes such as consistency of complete flake scars, position and percentage of cortex, number of negative flake scars, number of untruncated flake scars and the number of non-feather terminations. In order that morphometric data emphasise shape information rather

Table 9.1 Operational taxonomic units employed in analyses

Locality	n	Raw material
Attirampakkam, India	30	Quartzite
Bezez Cave (Level C), Adlun, Lebanon	30	Chert
Elveden, Suffolk, UK	24	Chert
Kariandusi, Kenya	30	Lava
Kharga Oasis (KO10c), Egypt	17	Chert
Lewa, Kenya	30	Lava
Olduvai Gorge (Bed II), Tanzania	13	Quartz, lava
Morgah, Pakistan	21	Quartzite
St Acheul, France	30	Chert
Tabun Cave (Ed), Israel	30	Chert

Total $n = 255$ handaxes

than mere size differences (which might reflect initial blank form and/or reduction intensity rather than socially transmitted factors influencing shape; see also Buchanan and Collard, this volume), variables 1–48 were size-adjusted via the geometric mean method (Jungers et al. 1995; Lycett et al. 2006). The geometric mean removes the confounding effect of isometric scale differences, equalizing the volume of each artefact while maintaining overall shape information (Falsetti et al. 1993; Jungers et al. 1995). Following size-adjustment, character data were converted into discrete states for the cladistic analyses via a statistical procedure termed “divergence coding” (Thorpe 1984). Divergence coding is a particularly useful approach since it not only accommodates the fact that attributes will vary both within and between OTUs (potentially even with some degree of overlap), but also assigns character states on the basis of statistically significant ($p \leq 0.05$) differences rather than arbitrary decisions or untested assumptions of similarity that might apply in the case of qualitative procedures (for further information see Lycett 2007b, 2009a). Screening of character data for non-phylogenetic integration via correlation analyses (see Lycett 2007b, 2009a for details) resulted in the removal of six characters (Characters 7, 11, 16, 35, 40, 43: Table 9.2), leaving 66 characters for the cladistic analyses. Parsimony trees were obtained in PAUP*4.0 (Swofford 1998) via the branch-and-bound algorithm, which is guaranteed to find the most parsimonious tree (Kitching et al. 1998). All characters were treated as ordered and freely reversing, as is appropriate for quantitative data of the type used here (Slowinski 1993; Rae 1997). Handaxes from Bed II Olduvai Gorge were used as an outgroup, since being the oldest artefacts in the data set (*ca.* 1.4–1.2 MYA) are most likely to be informative regarding the plesiomorphic characteristics of the handaxe assemblages used (Smith 1994: 58–59).

Figure 9.1 shows the cladogram produced by parsimony analysis of the handaxe data. An obvious attribute of this cladogram is that non-African assemblages form a monophyletic clade to the exclusion of African assemblages. A further attribute of note is that the two Near-Eastern assemblages of Bezez (Lebanon) and Tabun (Israel) are indicated to be sister taxa. The geographic and probable temporal proximity of these assemblages (Bar-Yosef 1994) intuitively supports the suggestion that the

Table 9.2 Characters employed in cladistic analyses

1. Core left width at 10% of length
2. Core left width at 20% of length
3. Core left width at 25% of length
4. Core left width at 30% of length
5. Core left width at 35% of length
6. Core left width at 40% of length
7. Core left width at 50% of length
8. Core left width at 60% of length
9. Core left width at 65% of length
10. Core left width at 70% of length
11. Core left width at 75% of length
12. Core left width at 80% of length
13. Core left width at 90% of length
14. Core right width at 10% of length
15. Core right width at 20% of length
16. Core right width at 25% of length
17. Core right width at 30% of length
18. Core right width at 35% of length
19. Core right width at 40% of length
20. Core right width at 50% of length
21. Core right width at 60% of length
22. Core right width at 65% of length
23. Core right width at 70% of length
24. Core right width at 75% of length
25. Core right width at 80% of length
26. Core right width at 90% of length
27. Core length distal at 10% of width
28. Core length distal at 20% of width
29. Core length distal at 25% of width
30. Core length distal at 30% of width
31. Core length distal at 40% of width
32. Core length distal at 50% of width
33. Core length distal at 60% of width
34. Core length distal at 70% of width
35. Core length distal at 75% of width
36. Core length distal at 80% of width
37. Core length distal at 90% of width
38. Core length proximal at 10% of width
39. Core length proximal at 20% of width
40. Core length proximal at 25% of width
41. Core length proximal at 30% of width
42. Core length proximal at 40% of width
43. Core length proximal at 50% of width
44. Core length proximal at 60% of width
45. Core length proximal at 70% of width
46. Core length proximal at 75% of width
47. Core length proximal at 80% of width

(continued)

Table 9.2 (continued)

48. Core length proximal at 90% of width
49. Coefficient of surface curvature 0–180°
50. Coefficient of surface curvature 90–270°
51. Coefficient of surface curvature 45–225°
52. Coefficient of surface curvature 135–315°
53. Coefficient of edge-point undulation
54. Index of symmetry
55. Maximum width/width at orientation
56. Maximum length/length at orientation
57. Nuclei outline length
58. Area of largest flake scar
59. CV of complete flake scar lengths
60. CV complete flake scar widths
61. Total number of complete (i.e. untruncated) flake scars
62. Total number of negative flake scars
63. Number of flakes removed superior and in contact with outline of nucleus
64. Number of non-feather terminations
65. % Cortex 1st superior quadrant
66. % Cortex 2nd superior quadrant
67. % Cortex 3rd superior quadrant
68. % Cortex 4th superior quadrant
69. % Cortex 1st inferior quadrant
70. % Cortex 2nd inferior quadrant
71. % Cortex 3rd inferior quadrant
72. % Cortex 4th inferior quadrant

Six characters (i.e. characters 7, 11, 16, 35, 40, and 43) were not employed due to integration (see Lycett 2009b for further details) leaving a total of 66 characters for the analyses

types of variable being used as characters in the phylogenetic analysis, are accurately determining phylogenetic relationships based on the proximity of socially transmitted information. The robustness of this relationship will be evaluated further below.

As noted earlier, how well a particular data set fits a tree model will depend on how useful the attributes inputted to the analysis are for this purpose, and to what degree they contain a "phylogenetic signal." One means of determining the strength of phylogenetic signal in a data set is to use a procedure termed "phylogenetic bootstrapping." This method involves randomly resampling the original character matrix and replacing some character states with alternatives. Usually a large number (≥1,000) of these pseudoreplicate character matrices are produced, and MP cladograms are determined for each of them. The results of these analyses are typically presented in the form of a majority-rule consensus tree, which indicates how many of the original instances of branching in the MP tree were also found in the bootstrap trees. Most commonly, this

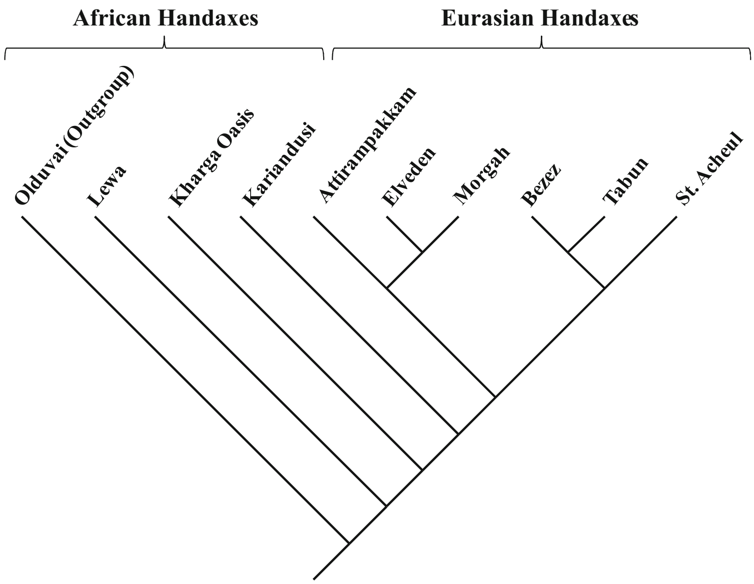

Fig. 9.1 Maximum parsimony cladogram based on 66 characters (Tree length = 1,222, ensemble Retention Index = 0.55)

is indicated by a percentage figure placed next to each instance of branching ("node" in cladistic terminology). The underlying logic here is that more robust data sets will provide a high number of nodes consistent with the original cladogram, whereas data sets containing relatively little phylogenetic signal will have fewer instances of branching consistent with the real MP tree. In the case of biological data sets, it has been suggested that where nodes are supported in at least 70% of the bootstrap trees, they may be considered robust (Hillis and Bull 1993).

Figure 9.2 shows a majority-rule consensus tree of 10,000 bootstrap trees obtained from the handaxe data set. It is noteworthy that the majority of nodes are supported at high levels (average bootstrap value = 87%). It is also important to note that the node indicating the branching of Eurasian handaxe assemblages from African assemblages is supported in 98% of the bootstrap trees, suggesting that the phylogeographic pattern noted earlier is robust. Likewise the sister-taxon relationship indicated by the MP tree for the two Near-Eastern assemblages (Bezez and Tabun) is supported in 100% of the bootstraps. Hence, it appears that the branching relationships of the MP cladogram are robustly supported by the character data.

A further useful means of measuring how well a particular data set fits a tree model is to look at the ensemble Retention Index, or RI value. This descriptive statistic measures goodness-of-fit by determining the number of homoplastic (i.e. non-parsimonious) character changes that occur in the MP tree independent of its length (Kitching et al. 1998). The RI ranges from 0.0 to 1.0, whereby a value of 1 equals a perfect goodness-of-fit, while values approaching 0 indicate poor goodness-of-fit to a tree model. Usefully, the Retention Index is not sensitive to differences

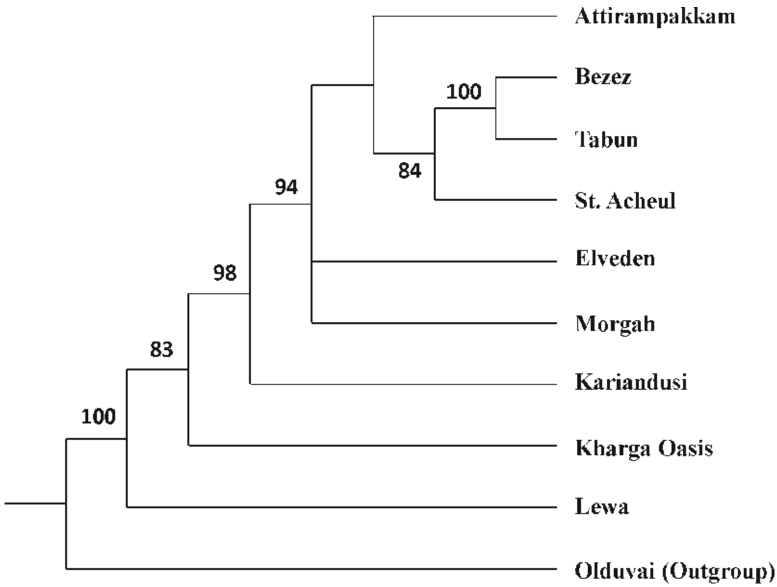

Fig. 9.2 50% majority-rule consensus bootstrap tree (based on 10,000 bootstrap replications). Numbers next to nodes indicate the percentage of bootstrap replications that support that branching relationship

between the dimensions of different character matrices, enabling RI values from different data sets to be compared.

Collard et al. (2006) recently employed the ensemble RI statistic to compare 20 cladograms produced from human cultural data sets of Holocene populations to equivalent cladograms generated for 21 biological data sets drawn from a range of behavioural, morphological and genetic studies of various non-human taxa. Their analyses indicated that, in the case of the cultural data sets, RIs ranged from 0.42 to 0.78 with a mean of 0.59. In the case of the biological data sets, RIs ranged from 0.35 to 0.94 with a mean of 0.61. Thus, contrary to what is often assumed, the human cultural data sets appeared to fit, on average, a tree model equally as well as biological data sets.

An RI value for the handaxe MP cladogram generated here may usefully be compared against Collard et al.'s (2006) results to test the relative goodness-of-fit to a tree model. An RI for the handaxe cladogram was computed in McClade 4.02 (Maddison and Maddison 2000) following importation of the data set from PAUP*4.0 (Swofford 1998). If the handaxe cladogram does not fit a tree model as well as those generated for the human cultural data sets examined by Collard and colleagues, we would expect the RI to fall close toward the lower end of, or even fall outside, the RI range for those data sets.

To the contrary, the RI value for the cladogram of handaxe assemblages was calculated at 0.55. This is well within the range of RI values reported by Collard et al. (2006) for human cultural data sets (0.42–0.78) and is very close to the mean of those data sets (0.59). Likewise, the handaxe cladogram RI falls within

the range of biological RIs reported by Collard and colleagues (0.35–0.94) and is again not drastically below the mean of those data sets (0.61). Hence, it would appear that in a comparative sense the handaxe assemblages fit a tree model equally as well as human cultural data sets from later periods and even biological data.

Even so, it might be argued that inputting a large database of metric characters such as that used here (i.e. 10 taxa × 66 characters) into a cladistic analysis automatically results in a relatively high RI value. To test this contention formally, 1,000 random character matrices of equal dimensions (i.e. an equal number of taxa, characters, and character states) were generated by reordering randomly the character states of the original matrix. MP trees for each of these 1,000 pseudoreplicate character matrices were determined and the RI for each of these trees recorded. It can be reasoned that if simply inputting a large data base into a cladistic analysis automatically results in an RI value similar to that found in the previous analysis, then the mean RI of these 1,000 random trees should be similar to that of the MP tree.

As noted above, the RI of the MP handaxe tree is 0.55. Conversely, the mean RI of 1,000 random trees was found to be only 0.20, with a range of 0.10–0.46. Hence, none of the random trees produced an RI value as high as that of the real data and the RI value of the handaxe cladogram is over twice as high as the mean RI of the 1,000 random trees. This provides strong evidence that the goodness-of-fit found for the handaxe assemblage cladogram is not a random (chance) result produced as a by-product of a relatively large data set of characters, but results from the internal properties of the data set itself.

As noted earlier, a potential concern in the application of phylogenetic methods to stone artefacts is the influence of raw material. The basic raw materials of the (ingroup) handaxe assemblages used here may be assigned to one of three broad categories: chert, quartzite or lava. A statistical test known as the Kishino–Hasegawa (1989) test may be used to determine if the MP handaxe cladogram is statistically different from a "model tree" that has been deliberately constrained by raw material factors. Thus, a model tree was built by first constructing a constraint tree reflecting pure raw material groups. This tree was constructed manually in MacClade 4.02 (Maddison and Maddison 2000). The constraint tree was then imported into PAUP*4.0 and a parsimony analysis conducted to find the cladogram most consistent with these raw material constraints (Fig. 9.3). The Kishino–Hasegawa (K–H) test uses the standard deviation of changes in each character in the cladogram and the t-statistic to determine if the true MP tree is statistically different ($p \leq 0.05$) from the model tree. If it is, then the parameter constraining the model tree (i.e. raw material) cannot reasonably be considered to be a dominant factor in producing the suggested relationships between taxa in the MP tree.

Table 9.3 shows the outcome of the K–H test. Differences between the MP cladogram and the raw material model tree were found to be highly significant ($p < 0.0001$). Hence, it does not appear that raw material is a dominant factor in producing the relationships between different handaxe assemblages in the MP cladogram.

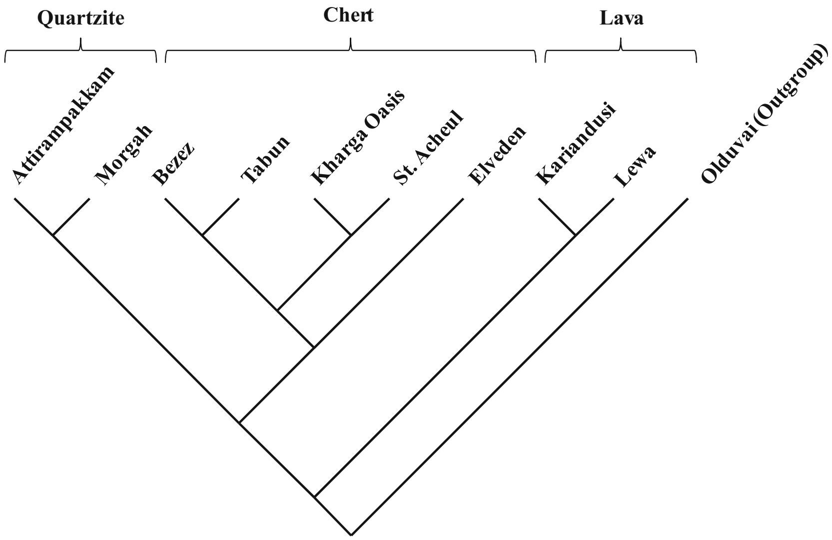

Fig. 9.3 Raw material model tree. The statistical differences between this tree and the Maximum Parsimony (MP) cladogram shown in Fig. 9.1 are highly significant ($p < 0.0001$), indicating that raw material factors do not have a dominant role in producing the relationships shown in the MP tree

Table 9.3 Results of K–H test

Tree	Length	Length difference	SD difference	*P*-value
1.	1,222	178	37.4	<0.0001
2.	1,400			

Tree 1 = Maximum parsimony topology; Tree 2 = Raw material model tree

Summary of Handaxe Cladistic Analyses

A series of analyses using cladistic procedures have indicated that Lower Palaeolithic data sets such as Acheulean handaxe assemblages can possess a strong phylogenetic signal, as predicted by cultural transmission theory. It has also been shown in this case study that the influence of raw material factors can be assessed. Such analyses indicated on this occasion that raw material is not a major determinant in producing the relationships shown in the cladogram. Interestingly, the cladogram appears to show a correlation between geography and phylogeny. Such correlations can particularly be seen in the robustly supported branching of Eurasian OTUs from African OTUs. Such phylogeographic patterning can be explained by dispersal factors as hominins migrated from Africa (Lycett 2009b). It has long been hypothesised that the Acheulean originated in sub-Saharan Africa and subsequently spread across many regions of the Palaeolithic Old World via hominin dispersals (Clark 1994; Carbonell et al. 1999; Goren-Inbar et al. 2000; Bar-Yosef and Belfer-Cohen 2001; Saragusti and Goren-Inbar 2001; Klein 2005). Such a hypothesis is precisely the

sort of question that population genetic approaches might allow us to test further. It is these methods that are discussed in the following section.

Population Genetic Models and Palaeolithic Variability

In biology, patterns of genetic and phenotypic variation reflect neutral forces of evolution (i.e. drift) and selective factors (either natural or artificial) to varying degrees. In the case of neutral evolution, variation is structured by mutation rates, gene-flow and dispersal (Wright 1931). Conversely, selection is reflected in instances wherever specific patterns of variation are related directly to increased survival and fecundity. Population genetics is the study of patterns of molecular variation against this context of selection, drift, mutation and gene flow (Crow and Kimura 1970; Gillespie 1998; Halliburton 2004). As such, population genetic approaches aim to examine the specific factors (e.g. drift, selection and population dispersal) that structure allelic variation.

A further corollary of cultural transmission theory is that many of the factors known to structure population-level patterns of genetic variation (e.g. population size, drift and dispersal) must also be considered when attempting to understand patterns of cultural variation (Neiman 1995; Lipo et al. 1997; Shennan 2000; Shennan and Wilkinson 2001; O'Brien and Lyman 2003b; Henrich 2004; Eerkens and Lipo 2005; Hamilton and Buchanan 2009; Lycett and Norton 2010). Again, it bears emphasising that this does not rely on an assumption that cultural and genetic transmission are identical in all aspects, most notably in regard to strict parent–offspring transmission in the case of genetics, contrasted with a diversity of potential transmission pathways in the case of culture. Rather, it is because both genetic transmission and cultural transmission are mechanisms of information transfer, demographic factors such as shifts in effective population size can have a strong statistical effect on resulting patterns of diversity in the transmitted phenomenon. (Note that the term "effective population size" here refers not necessarily to the total number of individuals in a given population, but to those individuals actually involved in the transmission process.)

As Mayr (1976: 26–28) has pointed out, "population thinking" – or the study of population variation – is yet another of those logical consequences that we owe directly to Darwin's theory of descent with modification and its three key pillars of inheritance, variation and sorting. As with phylogenetics, an implication of this is that principles and methods used to address these factors in genetic data may have utility when addressing analogous questions in cultural data (Cavalli-Sforza and Feldman 1981; Shennan 2001, 2006; Bentley et al. 2004, 2007; Richerson and Boyd 2005; Shennan and Bentley 2008; Mesoudi and Lycett 2009).

Looking at Dispersal, Drift and Selection in Acheulean Handaxes

While artefacts such as handaxes most certainly do not breed, the continued existence of handaxes, and to some extent parameters of handaxe variation through time, will be

influenced by factors affecting the *replicative success* (*sensu* Leonard and Jones 1987) of those ideas, skills, knowledge sets, etc. involved in their manufacture. The replicative success of such phenomena may be influenced by a variety of factors including stochastic processes (drift), natural selection and cultural (i.e. artificial) selection, the latter of which may or may not be intentionally directed by their manufacturers toward the patterns of variation or attributes concerned (for a more extended discussion of such issues in regard to handaxes see Lycett 2008).

Colleagues and I have previously used these principles to address questions surrounding Acheulean handaxes (Lycett and von Cramon-Taubadel 2008; Lycett 2008; Lycett and Norton 2010). In one of these studies (Lycett and von Cramon-Taubadel 2008), a formal population genetics model termed the "serial founder effect model" (sometimes also referred to as the "iterative founder effect model") was used to test the contention that handaxe manufacturing traditions were carried from Africa to wider parts of the Palaeolithic Old World via dispersal of Acheulean populations, as has long been hypothesised (e.g. Clark 1994; Carbonell et al. 1999; Goren-Inbar et al. 2000; Bar-Yosef and Belfer-Cohen 2001; Saragusti and Goren-Inbar 2001; Klein 2005). The serial founder effect model operates on the logic that as populations disperse over long distances, effective population sizes will become somewhat reduced with each episode of dispersal. In cases where the variation in a transmitted phenomenon is relatively neutral (i.e. not under strong selection), this will lead to a reduction of its within-group variance due to repeated instances of bottlenecking (i.e. reduction of effective population size and accompanying drift). Hence, in the case of genetic data, the model predicts a reduction of within-group genetic variance (σ^2) with increased geographic distance from a hypothesised point of origin (Fig. 9.4).

The serial founder effect model has recently been used with genetic data to test hypotheses regarding the dispersal of anatomically modern humans from Africa (Prugnolle et al. 2005; Ramachandran et al. 2005; Linz et al. 2007). These studies demonstrated a statistically significant fit between within-group genetic variance and increased geographic distance from Africa consistent with the predictions of the serial founder effect model. Subsequently, a fit to the model has also been supported using modern human craniometric data (Manica et al. 2007; von Cramon-Taubadel and Lycett 2008), demonstrating that phenotypic data can provide a proxy for parameters strictly transmitted and effected at a more proximate (i.e. genetic) level. In an intriguing application of the model (Linz et al. 2007), a fit has also been demonstrated in the case of human stomach bacteria (*Helicobacter pylori*), suggesting that the demographic consequences of human dispersal also had an effect on the population genetics of these transported populations of reproducing organisms, as humans carried them out of Africa in their stomachs.

Given the forgoing, an analogous situation in the case of handaxes would predict an inverse relationship between within-assemblage variance and increased geographic distance from East Africa, if the commonly assumed pattern of Acheulean dispersals from Africa is to be supported. Lycett and von Cramon-Taubadel (2008) tested this prediction using the ten handaxe assemblages listed earlier in Table 9.1. Mean within-assemblage variance was calculated using a series of 48 plan form

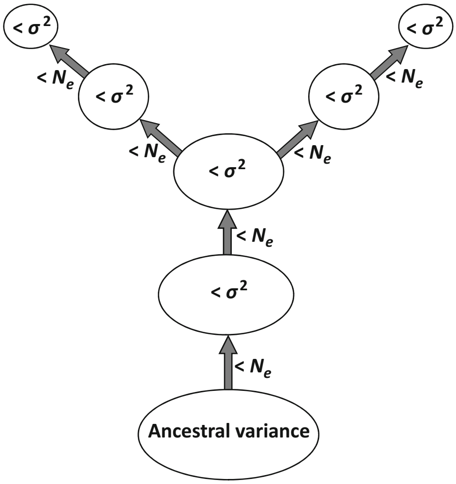

Fig. 9.4 Serial founder effect model. The model predicts a sequential reduction of within-group variance (σ^2) with increased distance from an hypothesized point of origin. This is due to repeated instances of a reduction in effective population size (N_e) along a dispersal route and subsequent drift (bottlenecking)

size-adjusted shape variables (Variables 1–48, Table 9.2). Two measures of geographic distance were used in their analyses: (1) "as-the-crow-flies" distances between East Africa (Olduvai Gorge, East Africa) and each site locality, and (2) the distances derived from a minimum spanning network linking site localities and two "waypoints" (Fig. 9.5). These latter distances were designed to approximate more closely the geographic distances covered by hominins in land-based scenarios of population dispersal(s) from Africa.

Lycett and von Cramon-Taubadel (2008) found statistically significant support for the serial founder effect model, with ~45–50% of within-assemblage handaxe shape variance explained by geographic distance from East Africa. Using a contrasting series of non-African start points, they found that no residual variation could be explained by a significant fit to the iterative founder effect model. Indeed, using non-African start points for the distance calculations did not merely produce non-significant results, but also generated R^2 values (range = 0.001–0.297) markedly different from those using the East-African origin (Lycett and von Cramon-Taubadel 2008: Table 9.3). Hence, using the non-African start points produced both weak and non-significant relationships (neither positive nor negative) between distance and within-assemblage variance patterns. These latter analyses are important since they suggest that the strength of relationship in their primary analysis is due to geographical parameters (i.e. African origin) rather than factors such as sampling bias. In the light of such analyses, it is interesting to reconsider the robustly supported phylogeographic pattern of Eurasian versus African assemblages found in the cladistic analyses presented earlier in this chapter. In combination, these analyses would appear to suggest that hominin dispersal patterns from Africa had an effect on

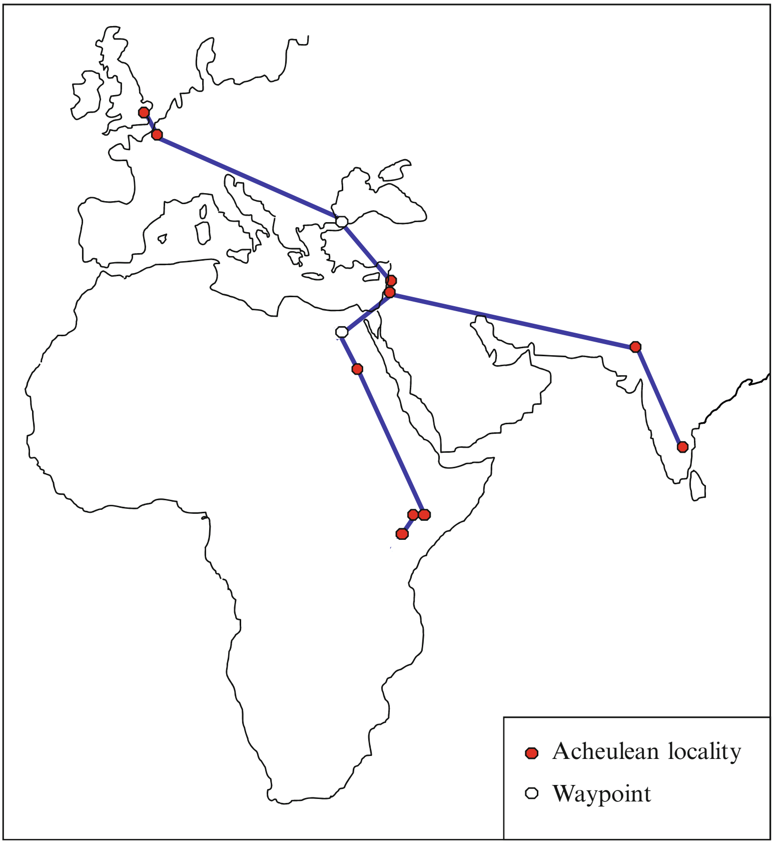

Fig. 9.5 Hypothetical dispersal route based on minimum-spanning network distances between Acheulean localities used in the analyses and two additional waypoints (Cairo, Egypt and Istanbul, Turkey). The waypoints were chosen in order to "anchor" the hypothesised dispersal route to a land-based pattern of dispersal

variation in certain handaxe parameters and, in turn, this led to a set of cladistic relationships that fit a phylogeographic pattern at broad levels.

More recently I extended these analyses to determine whether adding the property of handaxe symmetry to the data set either increased or decreased the fit to the serial founder effect model (Lycett 2008). As noted by Lycett and von Cramon-Taubadel (2008), their results imply that a high proportion of handaxe (plan-form) shape varies according to the principles of neutral drift, rather than being under strong directional selection. Again, drawing on principles applied in population genetics, it has recently been recognised that neutral (i.e. random) drift can provide a powerful null hypothesis for understanding patterns of artefactual and cultural change through time (see e.g. Bentley et al. 2004, 2007; Shennan 2006; Shennan and Bentley 2008; Mesoudi and Lycett 2009). In essence, if the null model of neutrality cannot be rejected, there is no requirement to invoke more complex selective

scenarios to account for particular patterns of artefactual variation and change. Thus, the results of Lycett and von Cramon-Taubadel's (2008) initial analyses provide a baseline of comparison against which other aspects of handaxe variability might usefully be assessed for their relative goodness-of-fit to a neutral model. Since it has often been suggested that handaxe symmetry may have been under selection for aesthetic, functional and/or adaptive reasons (e.g. Schick and Toth 1993; Kohn and Mithen 1999; Le Tensorer 2006), it was predicted that adding symmetry to the data set would decrease or possibly even destroy the fit to a serial founder effect model (Lycett 2008). Conversely, if handaxe symmetry variation was neutral, an equal or increased fit to the model would be expected. Such analyses demonstrated that adding the single variable of symmetry to the data set did indeed allow rejection of a null hypothesis of neutral variation, providing strong evidence that the property of symmetry variation in Acheulean handaxe was under strong influences of selection (Lycett 2008). Taken together, these nested analyses imply that different outline forms or "types" of handaxe (e.g. "cordiform," "pointed," "ovate," etc.) vary in a neutral manner, whereas regardless of which particular means (i.e. shape) a broadly symmetrical biface is achieved, the property of symmetry varies in a non-neutral manner and thus can be seen as subject to stronger selective forces. A neutral pattern of variation for handaxe outline shape would also be consistent with McPherron's (1999, 2003) assertion that a prominent source of variation in outline form is reduction intensity, although the neutral pattern is not mutually exclusive to additional sources of variation.

Using Population Genetic Principles to Determine the most Probable Route of Acheulean Dispersal

Here, I am going to apply these same general population genetic principles to determine whether one particular route of Acheulean dispersal from Africa is more probable than another. As noted earlier, Lycett and von Cramon-Taubadel (2008) found the strongest fit to the serial founder effect model when using a minimum-spanning network that linked Acheulean assemblage localities and two "waypoints" (Fig. 9.5). These two waypoints (Cairo, Egypt and Istanbul, Turkey) were chosen to deliberately "anchor" the hypothesised dispersal route to a land-based pattern of dispersal. However, alternative routes for Acheulean dispersal(s) have been hypothesised. In particular a "southern" route across the Arabian Peninsula has been suggested for populations dispersing into the Indian subcontinent (e.g. Whalen et al. 1989; Bar-Yosef and Belfer-Cohen 2001; Petraglia 2003; Derricourt 2005).

In order to assess the relative goodness-of-fit to this alternative dispersal route, a new minimum spanning network was constructed. This network linked the ten Acheulean localities and waypoints used by Lycett and von Cramon-Taubadel (2008), but also included two additional waypoints that constrained the dispersal of Acheulean hominins into southern Asia via a route across the Arabian Peninsula. The two waypoints chosen were Perim Island, Yemen (12.7N, 43.4E) and Dubai, United Arab

Emirates (25.3N, 55.3E). As shown in Fig. 9.6, this constrained the hypothesized dispersal pathway to a southern route, crossing what is currently the Bab al Mandab Strait between Djibouti and Yemen, and the narrowest point of the Arabian Gulf (i.e. the Strait of Hormuz). For purposes of direct comparison, the ten Acheulean artefact samples employed by Lycett and von Cramon-Taubadel (2008) were used here (Table 9.1), from which 48 plan-form variables were extracted (Variables 1–48, Table 9.2) and size-adjusted via the geometric mean method mentioned previously. Geographic distances were calculated in kilometres using great circle distances based on the haversine (see Lycett 2008). As a basic prediction it can be stated that if the southern dispersal route (Fig. 9.6) is more probable, then it should exhibit a higher relative goodness-of-fit to the serial founder effect model compared with the northern route going solely through the Sinai Peninsula (Fig. 9.5). This prediction was evaluated using least-squares regression, whereby the independent variable of mean within-assemblage variance was regressed on the dependent variable of geographic distance from East Africa (Olduvai Gorge). Hence, relative goodness-of-fit may be assessed

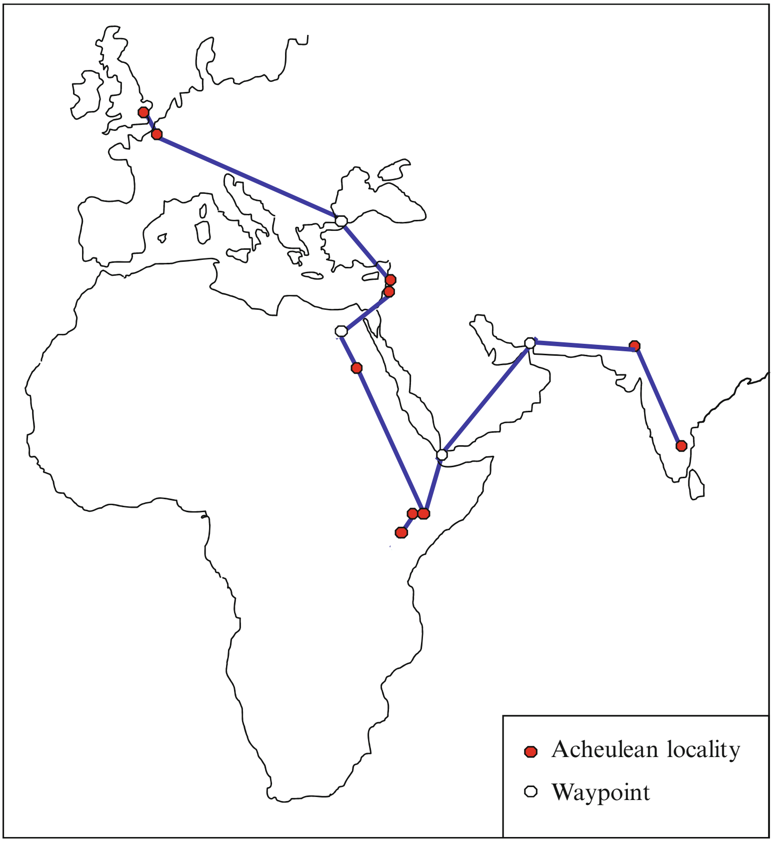

Fig. 9.6 Hypothesized dispersal route involving a "southern dispersal" of Acheulean populations across the Arabian Peninsula toward the Indian Subcontinent

for each route by direct comparison of the resultant coefficient of determination (R^2) values.

In the case of the northern (Sinai Peninsula) dispersal route, regression analyses produced an R^2 of 0.50 ($p = 0.023$). Conversely, the southern dispersal route produced an R^2 value of only 0.445 ($p = 0.035$). Hence, when using the northern dispersal route as much as 50% of within assemblage variance could be accounted for by the serial founder effect model, whereas in the case of the southern dispersal route less than 45% of within assemblage variance was explained by the model. Indeed, the goodness-of-fit in the case of the southern dispersal route was actually less than that obtained by Lycett and von Cramon-Taubadel (2008) when using crude "as-the-crow-flies" distances ($R^2 = 0.452$, $p = 0.033$), which we know to be improbable as routes for hominin dispersal.

The results of this comparative analysis thus appear to indicate that the southern route for Acheulean dispersals was less probable than that of a northern dispersal route via the Sinai Peninsula. Interestingly, Derricourt (2005) has previously suggested that the most parsimonious scenario for Plio-Pleistocene hominin dispersals is one that does not require an ability to make water crossings. Current evidence suggests that well before the appearance of Acheulean technologies in Africa, land-bridges across the Bab al Mandab Strait would have ceased to exist (Fernandes et al. 2006), thus requiring the crossing of a waterway by Acheulean hominins if used as a dispersal route. The analyses undertaken here support the view of Derricourt (2005) that in the absence of strong evidence to the contrary, dispersal routes not involving the crossing of waterways should be treated as a null hypothesis.

Discussion

In this paper I have attempted to show how principles and methodologies derived from biology (descent with modification, population thinking, phylogenetics and population genetic models) can profitably be employed in lithic studies, particularly in the case of Lower and Middle Palaeolithic data where, currently, such theoretical and methodological approaches appear to be less frequently applied. A series of phylogenetic analyses applied to a database of Acheulean handaxes revealed a phylogeographic pattern. It was also shown via bootstrap and randomization procedures that this relationship was robustly supported, and that the handaxe data fit a phylogenetic model equally as well as a comparative set of later human cultural and biological data sets. It was also demonstrated via statistical procedures that raw material was not a dominant factor in producing the relationships indicated by the cladogram. Population genetic approaches confirmed that the source of this basic phylogeographic pattern appears to have been mediated by patterns of hominin dispersal. These latter analyses also showed how formal models drawn from population genetics can provide explicit and testable predictions for lithic artefactual data sets, including what might be expected under alternative potential routes of hominin dispersal. Of course, there are doubtless ways in which the resolution and

quality of the empirical data employed here might be bettered. Indeed, future studies might refine, improve upon, or even refute some of the results and conclusions presented here: such is the nature of scientific progress. However, these scopes for improvement lie more in the realm of empirical parameters rather than with the general theoretical and methodological framework advocated.

One potential area that might provide particular scope for expansion in future studies is in developing a greater understanding between artefact life history and technological evolution. As Shott notes elsewhere in this volume, the breakage of stone is an absolute prerequisite to the manufacture of any knapped lithic artefact. As such, a stone tool's "life-history"[2] extends from the first flake removed from a core through to any potential resharpening and usewear that occurs prior to final discard. As noted here and elsewhere (e.g. Buchanan and Collard 2007) those advocating the application of phylogenetic and population genetic models to lithic data have not been entirely ignorant of such matters, employing sophisticated methods of size-adjustment to remove the confounding effect of size differences that might occur through reduction and resharpening, especially toward the end of an artefact's life history (Lycett et al. 2006; see also Buchanan and Collard, this volume). However, there may be a possibility to more actively integrate artefact reduction sequences (ontogeny) and patterns of technological evolution (see also, Riede 2006), in a similar manner to the way in which evolution and development (so-called "Evo–Devo") studies in biology have embraced both individual life histories and an understanding of long-term evolutionary trajectories (e.g. Raff 2000; Telford and Budd 2003).

Elsewhere, I have shown that the long-held view that Mode 1 style cores became elaborated into bifaces, and that ultimately bifaces are close technological relatives of Levallois cores, can be demonstrated through the use of phylogenetic methods (Lycett 2007b). As such, there is some "recapitulation" of the ontogenetic development of a Levallois core in the phylogenetic relationships between Mode 1, Mode 2, and Mode 3 style artefacts. I mention this here not because the ontogeny of lithic artefacts will always recapitulate their phylogeny any more so than in the case of biology, where it has been recognised that this will occur in some cases but not others (Gould 1977). (Although it is in itself a valuable exercise to document where this does and does not occur.) Rather, it is because the "Evo–Devo" approach has shown that major episodes of evolutionary change are frequently brought about by manipulation of specific developmental stages (Raff 2000; Arthur 2004). Over recent years, there has been much debate as to whether the study of reduction sequences and the *chaîne opératoire* of lithic artefacts are of strong analytical use or more descriptive and typological procedures (e.g. Shott 2003; Bar-Yosef and Van Peer 2009). Combining insights from experiment, refitting, reduction, morphometrics and phylogeny might provide equivalent insights as to how the manipulation of specific ontogenetic stages in reduction led to changes in lithic technological evolution.

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[2] In the case of stone tool "life history," a useful distinction may be made between "ontogeny" (the reduction process leading up to the point of first usage) and "senility" (factors such as resharpening and use wear that take place following first use).

Conclusion

The late Glynn Isaac (1977: 207) once commented that:

> Most Palaeolithic archaeologists in general, myself included, tend to believe that the assemblages of humanly flaked stones that we recover in quantities from sites such as Olorgesailie preserve a great deal of valuable information about the craft traditions, the cultural affinities, and the economic life of the hominids who made them ... It sometimes appears that all of us treat stone artefacts as infinitely complex repositories of palaeocultural information and assume that it is only the imperfections of our present analytical systems that prevent us from decoding them. But is this really so?

Analyses such as those presented here might go some way to reaffirming that this indeed *is* so. Yet, Isaac's remark that it might be "the imperfections of our present analytical systems that prevent us from decoding" such cultural information is particularly interesting in regard to the issues discussed in this paper, and more widely in the present volume. Some of the data accumulated by archaeologists and the way data accumulation is approached may not currently be in a format that is most suitable for addressing questions of this nature. Similar concerns were, of course, also stated by David Clarke (1968) who, as noted in the introduction of this volume, urged archaeologists to find more detailed means of extracting information from their available data. Nevertheless, recent developments (e.g. Tostevin 2003; Buchanan 2006; Clarkson et al. 2006; Lycett et al. 2006; as well as several papers in this volume) suggest that large and detailed comparative multivariate data sets can be obtained. Armed with the ontological framework provided by cultural transmission theory, its associated battery of analytical techniques, and by the rich data that such new methodological developments provide, we may be on the brink of some exciting discoveries regarding the evolution of Palaeolithic technologies.

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References

Adrain, J.M., Edgecombe, G.D., and Lieberman, B.S. (Eds.), 2001. *Fossils, Phylogeny and Form: An Analytical Approach*. Kluwer/Plenum Press, New York.

Arthur, W., 2004. The effect of development on the direction of evolution: toward a twenty-first century consensus. *Evolution & Development* 6: 282–288.

Asfaw, B., Beyene, Y., Suwa, G., Walter, R.C., White, T.D., WoldeGabriel, G. and Yemane, T., 1992. The earliest Acheulean from Konso-Gardula. *Nature* 360: 732–735.

Bar-Yosef, O., 1994. The lower paleolithic of the Near East. *Journal of World Prehistory* 8: 211–265.

Bar-Yosef, O. and Belfer-Cohen, A., 2001. From Africa to Eurasia – early dispersals. *Quaternary International* 75: 19–28.

Bar-Yosef, O. and Van Peer, P., 2009. The *chaîne opératoire* approach in Middle Palaeolithic archaeology. *Current Anthropology* 50: 103–131.
Bentley, R.A., Hahn, M.W. and Shennan, S., 2004. Random drift and culture change. *Proceedings of the Royal Society of London B* 271: 1443–1450.
Bentley, R.A., Lipo, C.P., Herzog, H.A. and Hahn, M.W., 2007. Regular rates of popular culture change reflect random copying. *Evolution and Human Behavior* 28: 151–158.
Bettinger, R.L. and Eerkens, J., 1999. Point typologies, cultural transmission, and the spread of bow-and-arrow technology in the prehistoric Great Basin. *American Antiquity* 64: 231–242.
Biro, D., Sousa, C. and Matsuzawa, T., 2006. Ontogeny and cultural propagation of tool use by wild chimpanzees at Bossou, Guinea: case studies in nut cracking and leaf folding. In *Cognitive Development in Chimpanzees*, edited by T. Matsuzawa, M. Tomonaga and M. Tanaka, pp. 476–508. Springer, New York.
Binford, L.R., 1973. Interassemblage variability – the Mousterian and the functional argument. In *The Exploration of Culture Change*, edited by C. Renfrew, pp. 227–254. University of Pittsburgh Press, Pittsburgh.
Bonnie, K.E., Horner, V., Whiten, A., and de Waal, F.B.M., 2007. Spread of arbitrary conventions among chimpanzees: A controlled experiment. *Proceedings of the Royal Society B* 274: 367–372.
Bordes, F., 1961. *Typologie de Paléolithique Ancien et Moyen*. Delmas, de l'Université de Bordeaux 1. Bordeaux.
Buchanan, B., 2006. An analysis of Folsom projectile point resharpening using quantitative comparisons of form and allometry. *Journal of Archaeological Science* 33: 185–199.
Buchanan, B. and Collard, M., 2007. Investigating the peopling of North America through cladistic analyses of Early Paleoindian projectile points. *Journal of Anthropological Archaeology* 26: 366–393.
Buchanan, B. and Collard, M., 2008. Phenetics, cladistics, and the search for the Alaskan ancestors of the Paleoindians: a reassessment of relationships among the Clovis, Nenana, and Denali archaeological complexes. *Journal of Archaeological Science* 35: 1683–1694.
Carbonell, E., Mosquera, M., Xose, P.R. and Sala, R. 1999. Out of Africa: the dispersal of the earliest technical systems reconsidered. *Journal of Anthropological Archaeology* 18: 119–136.
Cavalli-Sforza, L.L. and Feldman, M.W., 1981. *Cultural Transmission and Evolution: A Quantitative Approach*. Princeton University Press, Princeton, NJ.
Clark, J.D., 1994. The Acheulian industrial complex in Africa and elsewhere. In *Integrative Paths to the Past*, edited by R.S. Corruccini and R.L. Ciochon, pp. 451–469. Prentice Hall, Englewood Cliffs, NJ.
Clarke, D.L., 1968. *Analytical Archaeology*. Methuen, London.
Clarkson, C., Vinicius, L. and Lahr, M.M., 2006. Quantifying flake scar patterning on cores using 3D recording techniques. *Journal of Archaeological Science* 33: 132–142.
Collard, M. and Shennan, S., 2000. Processes of cultural change in prehistory: a case study from the European Neolithic. In *Archaeogenetics: DNA and the Population Prehistory of Europe*, edited by C. Renfrew and K. Boyle, pp. 89–97. McDonald Institute for Archaeological Research, Cambridge.
Collard, M., Shennan, S.J. and Tehrani, J.J., 2006. Branching, blending, and the evolution of cultural similarities and differences among human populations. *Evolution and Human Behavior* 27: 169–184.
Crow, J.F. and Kimura, M., 1970. *Introduction to Population Genetics Theory*. Harper & Row, New York.
Darwent, J. and O'Brien, M.J., 2006. Using cladistics to reconstruct lineages of projectile points from northeastern Missouri. In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory* edited by C.P. Lipo, M.J. O'Brien, M. Collard and S. Shennan, pp. 185–208. Aldine Transaction, New Brunswick, NJ.
Darwin, C., 1859. *On the Origin of Species*. John Murray, London.
Derricourt, R., 2005. Getting "out of Africa": sea crossings, land crossings and culture in the hominin migrations. *Journal of World Prehistory* 19: 119–132.

Dibble, H.L., 1987. The interpretation of Middle Paleolithic scraper morphology. *American Antiquity* 52: 109–117.

Eerkens, J.W. and Lipo, C.P., 2005. Cultural transmission, copying errors, and the generation of variation in material culture and the archaeological record. *Journal of Anthropological Archaeology* 24: 316–334.

Eerkens, J.W. and Lipo, C.P., 2007. Cultural transmission theory and the archaeological record: context to understanding variation and temporal changes in material culture. *Journal of Archaeological Research* 15: 239–274.

Eldredge, N. and Cracraft, J., 1980. *Phylogenetic Patterns and the Evolutionary Process*. Columbia University Press, New York.

Falsetti, A.B., Jungers, W.L. and Cole III, T.M., 1993. Morphometrics of the Callitrichid forelimb: a case study in size and shape. *International Journal of Primatology* 14: 551–572.

Fernandes, C.A., Rohling, E.J. and Siddall, M., 2006. Absence of post-Miocene Red Sea land bridges: biogeographic implications. *Journal of Biogeography* 33: 961–966.

Foley, R.A., 1987. Hominid species and stone tool assemblages: how are they related? *Antiquity* 61: 380–392.

Gee, H., 2000. *Deep Time: Cladistics, The Revolution in Evolution*. Fourth Estate, London.

Gillespie, J.H., 1998. *Population Genetics: A Concise Guide*. Johns Hopkins Press, Baltimore, MD.

Goodman, M.E., 1944. The physical properties of stone tool materials. *American Antiquity* 9: 415–433.

Goren-Inbar, N., Feibel, C.S., Verosub, K.L., Melamed, Y., Kislev, M.E., Tchernov, E. and Saragusti, I., 2000. Pleistocene milestones on the out-of-Africa corridor at Gesher Benot Ya'aqov, Israel. *Science* 289: 944–947.

Gould, S.J., 1977. *Ontogeny and Phylogeny*. Harvard University Press, Cambridge, MA.

Gowlett, J.A.J., 2006. The elements of design form in Acheulian bifaces: modes, modalities, rules and language. In *Axe Age: Acheulian Tool-Making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 203–221. Equinox, London.

Halliburton, R., 2004. *Introduction to Population Genetics*. Prentice Hall, Upper Saddle River, NJ.

Hamilton, M.J. and Buchanan, B., 2009. The accumulation of stochastic copying errors causes drift in culturally transmitted technologies: quantifying Clovis evolutionary dynamics. *Journal of Anthropological Archaeology* 28: 55–69.

Harmon, M.J., Van Pool, T.L., Leonard, R.D., Van Pool, C.S. and Salter, L.A., 2006. Reconstructing the flow of information across time and space: a phylogenetic analysis of ceramic traditions from prehispanic western and northern Mexico and the American southwest. In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory* edited by C.P. Lipo, M.J. O'Brien, M. Collard and S. Shennan, pp. 209–229. Aldine Transaction, New Brunswick, NJ.

Henrich, J., 2004. Demography and cultural evolution: how adaptive cultural processes can produce maladaptive losses – the Tasmanian case. *American Antiquity* 69: 197–214.

Hillis, D.M. and Bull, J.J., 1993. An empirical test of bootstrapping as a method for assessing confidence in phylogenetic analysis. *Systematic Biology* 42: 182–192.

Hopper, L.M., Spiteri, A., Lambeth, S.P., Schapiro, S.J., Horner, V. and Whiten, A., 2007. Experimental studies of tradition and underlying transmission processes in chimpanzees. *Animal Behaviour* 73: 1021–1032.

Horner, V., Whiten, A., Flynn, E. and de Waal, F.B.M., 2006. Faithful replication of foraging techniques along cultural transmission chains by chimpanzees and children. *Proceedings of the National Academy of Sciences of the United States of America* 103: 13878–13883.

Isaac, G.L., 1977. *Olorgesailie: Archaeological Studies of a Middle Pleistocene Lake Basin in Kenya*. University of Chicago Press, Chicago.

Jordan, P. and Shennan, S., 2003. Cultural transmission, language, and basketry traditions amongst the California Indians. *Journal of Anthropological Archaeology* 22: 42–74.

Jordan, P. and Mace, T., 2006. Tracking culture-historical lineages: can 'descent with modification' be linked to 'association by descent'? In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory* edited by C.P. Lipo, M.J. O'Brien, M. Collard and S. Shennan, pp. 149–167. Aldine Transaction, New Brunswick, NJ.

Jungers, W.L., Falsetti, A.B. and Wall, C.E., 1995. Shape, relative size, and size adjustments in morphometrics. *Yearbook of Physical Anthropology* 38: 137–161.

Kishino, H. and Hasegawa, M., 1989. Evaluation of the maximum likelihood estimate of the evolutionary tree topologies from DNA sequence data, and the branching order in Hominoidea. *Journal of Molecular Evolution* 29: 170–179.

Kitching, I.J., Forey, P.L., Humphries, C.J. and Williams, D.M., 1998. *Cladistics: The Theory and Practice of Parsimony Analysis*. Oxford University Press, Oxford.

Klein, R., 2005. Hominin dispersal in the Old World. In *The Human Past: World Prehistory and the Development of Human Societies*, edited by C. Scarre, pp. 84–123. Thames & Hudson, London.

Kohn, M. and Mithen, S., 1999. Handaxes: products of sexual selection? *Antiquity* 73: 518–526.

Kuhn, S.L., 2004. Evolutionary perspectives on technology and technological change. *World Archaeology* 36: 561–570.

Leonard, R.D. and Jones, G.T., 1987. Elements of an inclusive evolutionary model for archaeology. *Journal of Anthropological Archaeology* 6: 199–219.

Le Tensorer, J.-M., 2006. Les cultures acheuléennes et la question de l'émergence de la pensée symbolique chez Homo erectus à partir des données relatives à la forme symétrique et harmonique des bifaces. *C R Palevol* 5: 127–135.

Linz, B., Balloux, F., Moodley, Y., Manica, A., Liu, H., Roumagnac, P., Falush, D., Stamer, C., Prugnolle, F., van der Merwe, S.W., Yamaoka, Y., Graham, D.Y., Perez-Trallero, E., Wadstrom, T., Suerbaum, S. and Achtman, M., 2007. An African origin for the intimate association between humans and *Helicobacter pylori*. *Nature* 445: 915–918.

Lipo, C.P., Madsen, M.E., Dunnell, R.C. and Hunt, T., 1997. Population structure, cultural transmission, and frequency seriation. *Journal of Anthropological Archaeology* 16: 301–333.

Lipo, C.P., O'Brien, M.J., Collard, M. and Shennan, S.J., 2006. Cultural phylogenies and explanation: Why historical methods matter. In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory*, edited by C.P. Lipo, M.J. O'Brien, M. Collard and S.J. Shennan, pp. 3–16. Aldine Transaction, New Brunswick, NJ.

Lycett, S.J., 2007a. Is the Soanian techno-complex a Mode 1 or Mode 3 phenomenon? A morphometric assessment. *Journal of Archaeological Science* 34: 1434–1440.

Lycett, S.J., 2007b. Why is there a lack of Mode 3 Levallois technologies in East Asia? A phylogenetic test of the Movius-Schick hypothesis. *Journal of Anthropological Archaeology* 26: 541–575.

Lycett, S.J., 2008. Acheulean variation and selection: does handaxe symmetry fit neutral expectations? *Journal of Archaeological Science* 35: 2640–2648.

Lycett, S.J., 2009a. Are Victoria West cores 'proto-Levallois'? A phylogenetic assessment. *Journal of Human Evolution* 56: 175–191.

Lycett, S.J., 2009b. Understanding ancient hominin dispersals using artefactual data: a phylogeographic analysis of Acheulean handaxes. *PLoS ONE* 4/e7404: 1–6.

Lycett, S.J. and Gowlett, J.A.J., 2008. On questions surrounding the Acheulean 'tradition'. *World Archaeology* 40: 295–315.

Lycett, S.J. and Norton, C.J. 2010. A demographic model for Palaeolithic technological evolution: the case of East Asia and the Movius Line. *Quaternary International* 211: 55–65.

Lycett, S.J. and von Cramon-Taubadel, N., 2008. Acheulean variability and hominin dispersals: a model-bound approach. *Journal of Archaeological Science* 35: 553–562.

Lycett, S.J., Collard, M. and McGrew, W.C., 2007. Phylogenetic analyses of behavior support existence of culture among wild chimpanzees. *Proceedings of the National Academy of Sciences of the United States of America* 104: 17588–17592.

Lycett, S.J., von Cramon-Taubadel, N. and Foley, R.A., 2006. A crossbeam co-ordinate caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33: 847–861.

Lycett, S.J., Collard, M. and McGrew, W.C., 2009. Cladistic analyses of behavioral variation in wild *Pan troglodytes*: exploring the chimpanzee culture hypothesis. *Journal of Human Evolution* 57: 337–349.

Lyman, R.L., VanPool, T.L. and O'Brien, M.J., 2008. Variation in North American dart points and arrow points when one or both are present. *Journal of Archaeological Science* 35: 2805–2812.

Lyman, R.L., VanPool, T.L. and O'Brien, M.J., 2009. The diversity of North American projectile-point types, before and after the bow and arrow. *Journal of Anthropological Archaeology*. 28: 1–13.

Maddison, D.R. and Maddison, W.P., 2000. *MacClade 4: Analysis of Phylogeny and Character Evolution – Users' Handbook*. Sinauer Associates, Sunderland, MA.

Manica, A., Amos, W., Balloux, F. and Hanihara, T., 2007. The effect of ancient population bottlenecks on human phenotypic variation. *Nature* 448: 346–349.

Mayr, E., 1976. Typological versus population thinking. In *Evolution and the Diversity of Life*, edited by E. Mayr, pp. 26–29. Harvard University Press. Reprinted from: pp. 409–412 of 'Darwin and the evolutionary theory in biology'. In *Evolution and Anthropology: A Centennial Appraisal* (Washington, DC.: The Anthropological Society of Washington, 1959), Cambridge, MA.

Mayr, E., 1982. *The Growth of Biological Thought*. Harvard University Press, Cambridge, MA.

McBrearty, S., 2003. Patterns of technological change at the origin of *Homo sapiens*. *Before Farming* 3: 1–5.

McGrew, W.C., 2004. *The Cultured Chimpanzee: Reflections on Cultural Primatology*. Cambridge University Press, Cambridge.

McLennan, D.A. and Brooks, D.R., 2001. Phylogenetic systematics: five steps to enlightenment. In *Fossils, Phylogeny and Form: An Analytical Approach*, edited by J.M. Adrain, G.D. Edgcombe and B.S. Lieberman, pp. 7–28. Kluwer Academic/Plenum, New York.

McPherron, S.P., 1999. Ovate and pointed handaxe assemblages: two points make a line. *Préhistoire Européenne* 14: 9–32.

McPherron, S.P., 2003. Technological and typological variability in bifaces from Tabun Cave, Israel. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H. L. Dibble, pp. 55–75. University of Pennsylvania, Philadelphia, PA.

Mellars, P., 1970. Some comments on the notion of 'functional variability' in stone-tool assemblages. *World Archaeology* 2: 74–89.

Mesoudi, A. and Lycett, S.J., 2009. Random copying, frequency-dependent copying and culture change. *Evolution and Human Behavior* 30: 41–48.

Mesoudi, A. and O'Brien, M.J., 2008a. The cultural transmission of Great Basin projectile point technology I: an experimental simulation. *American Antiquity* 73: 3–28.

Mesoudi, A. and O'Brien, M.J., 2008b. The cultural transmission of Great Basin projectile point technology II: an agent-based computer simulation. *American Antiquity* 73: 627–644.

Mesoudi, A., Whiten, A. and Laland, K.N., 2006. Towards a unified science of cultural evolution. *Behavioral and Brain Sciences* 29: 329–383.

Mithen, S., 1996. Social learning and cultural tradition: interpreting early Palaeolithic technology. In *The Archaeology of Human Ancestry: Power, Sex and Tradition*, edited by J. Steele and S. Shennan, pp. 207–229. Routledge, London.

Mithen, S., 1999. Imitation and cultural change: a view from the Stone Age, with specific reference to the manufacture of handaxes. In *Mammalian Social Learning: Comparative and Ecological Perspectives*, edited by H.O. Box and K.R. Gibson, pp. 389–399. Cambridge University Press, Cambridge.

Neiman, F.D., 1995. Stylistic variation in evolutionary perspective: inferences from decorative diversity and interassemblage distance in Illinois Woodland ceramic assemblages. *American Antiquity* 60: 7–36.

Oakley, K.P., 1958. *Man the Tool-Maker*, 4th Edition. Trustees of the British Museum, London.

O'Brien, M.J. and Lyman, R.L., 2000. *Applying Evolutionary Archaeology: A Systematic Approach*. Kluwer Academic/Plenum, New York.

O'Brien, M.J. and Lyman, R.L., 2003a. *Cladistics and Archaeology*. University of Utah Press, Salt Lake City, Utah.

O'Brien, M.J. and Lyman, R.L., 2003b. Style, function, transmission; an introduction. In *Style, Function, Transmission*, edited by M.J. O'Brien and R.L. Lyman, pp. 1–32. University of Utah Press, Salt Lake City.

O'Brien, M.J., Darwent, J. and Lyman, R.L., 2001. Cladistics is useful for reconstructing archaeological phylogenies: Palaeoindian points from the southeastern United States. *Journal of Archaeological Science* 28: 1115–1136.

O'Brien, M.J., Lyman, R.L., Collard, M., Holden, C.J., Gray, R.D. and Shennan, S., 2008. Transmission, phylogenetics, and the evolution of cultural diversity. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M.J. O'Brien, pp. 39–58. Society for American Archaeology Press, Washington, DC.

Otte, M., 2003. The pitfalls of using bifaces as cultural markers. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H.L. Dibble, pp. 183–192.University of Pennsylvania, Philadelphia, PA.

Page, R.D.M. and Holmes, E.C., 1998. *Molecular Evolution: A Phylogenetic Approach*. Blackwell Science, Oxford.

Petraglia, M.D., 2003. The Lower Palaeolithic of the Arabian Peninsula: occupations, adaptations, and dispersals. *Journal of World Prehistory* 17: 141–179.

Prugnolle, F., Mancia, A. and Balloux, F., 2005. Geography predicts neutral genetic diversity of human populations. *Current Biology* 15: 159–160.

Ramachandran, S., Deshpande, O., Roseman, C.C., Rosenberg, N.A., Feldman, M.W. and Cavalli-Sforza, L.L. 2005. Support from the relationship of genetic and geographic distance in human populations for serial founder effect originating in Africa. *Proceedings of the National Academy of Sciences of the United States of America* 102: 15942–15947.

Quicke, D.L.J., 1993. *Principles and Techniques of Contemporary Taxonomy*. Blackie Academic & Professional, London.

Rae, T.C., 1997. The early evolution of the hominoid face. In *Function, Phylogeny, and Fossils: Miocene Hominoid Evolution and Adaptations*, edited by D.R. Begun, C.V. Ward, M.D. Rose, pp. 59–77. Plenum Press, New York.

Raff, R.A., 2000. Evo-devo: the evolution of a new discipline. *Nature Reviews: Genetics* 1: 74–79.

Richerson, P.J. and Boyd, R., 2005. *Not by Genes Alone: How Culture Transformed Human Evolution*. University of Chicago Press, Chicago.

Riede, F., 2006. *Chaîne opératoire, chaîne evolutionare*? Putting technological sequences into an evolutionary perspective. *Archaeological Review from Cambridge* 21: 50–75.

Riede, F., 2008. The Laacher See-eruption (12,920 BP) and material culture change at the end of the Allerød in Northern Europe. *Journal of Archaeological Science* 35: 591–599.

Roe, D., 1976. Typology and the trouble with handaxes. In *Problems in Economic and Social Archaeology*, edited by G. de Sieveking, I.H. Longworth and K.E. Wilson, pp. 61–70. Duckworth, London.

Saragusti, I. and Goren-Inbar, N., 2001. The biface assemblage from Gesher Benot Ya'aqov, Israel: illuminating patterns in 'Out of Africa' dispersal. *Quaternary International* 75: 85–89.

Schick, K.D. and Toth, N., 1993. *Making Silent Stones Speak: Human Evolution and the Dawn of Human Technology*. Weidenfeld and Nicolson, London.

Shennan, S., 2000. Population, culture history, and the dynamics of culture change. *Current Anthropology* 41: 811–835.

Shennan, S., 2001. Demography and cultural innovation: a model and its implications for the emergence of modern human culture. *Cambridge Archaeological Journal* 11: 5–16.

Shennan, S., 2006. From cultural history to cultural evolution: an archaeological perspective on social information transmission. In *Social Information Transmission and Human Biology*, edited by J.C.K. Wells, S. Strickland, K. Laland, pp. 173–189. Taylor & Francis, New York.

Shennan, S.J. and Bentley, R.A., 2008. Style, interaction, and demography among the earliest farmers of central Europe. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M.J. O'Brien, pp. 164–177. Society for American Archaeology Press, Washington, DC.

Shennan, S.J. and Steele, J., 1999. Cultural learning in hominids: a behavioural ecological approach. In *Mammalian Social Learning: Comparative and Ecological Perspectives*, edited by H.O. Box, K.R. Gibson, pp. 367–388. Cambridge University Press, Cambridge.

Shennan, S.J. and Wilkinson, J.R., 2001. Ceramic style change and neutral evolution: a case study from Neolithic Europe. *American Antiquity* 66: 577–593.

Shott, M.J., 2003. *Chaîne opératoire* and reduction sequence. *Lithic Technology* 28: 95–105.

Shott, M.J., 2008. Darwinian evolutionary theory and lithic analysis. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M.J. O'Brien, pp. 146–157. Society for American Archaeology Press, Washington, DC.

Slowinski, J.B., 1993. 'Unordered' versus 'ordered' characters. *Systematic Biology* 42: 155–165.

Smith, A.B., 1994. *Systematics and the Fossil Record*. Blackwell Science, Oxford.

Sober, E., 1983. Parsimony in systematics: philosophical issues. *Annual Review of Ecology and Systematics* 14: 335–357.

Stout, D., 2002. Skill and cognition in stone tool production. *Current Anthropology* 43: 693–722.

Stout, D., 2005. The social and cultural context of stone knapping skill acquisition. In *Stone Knapping: The Necessary Conditions for a Uniquely Hominin Behavior*, edited by V. Roux and B. Bril, pp. 331–340. McDonald Institute for Archaeological Research, Cambridge.

Swofford, D.L., 1998. *PAUP*: Phylogenetic Analysis Using Parsimony (*and Other Methods)*, Version 4.0. Sinauer Associates, Sunderland, MA.

Tehrani, J.J. and Collard, M., 2002. Investigating cultural evolution through biological phylogenetic analyses of Turkmen textiles. *Journal of Anthropological Archaeology* 21: 443–463.

Tehrani, J.J. and Collard, M., 2009. On the relationship between inter-individual cultural transmission and inter-group cultural diversity: a case study of weaving in Iranian tribal populations. *Evolution and Human Behavior* 30: 286–300.

Telford, M.J. and Budd, G.E. 2003. The place of phylogeny and cladistics in Evo-Devo research. *International Journal of Developmental Biology* 47: 479–490.

Thorpe, R.S., 1984. Coding morphometric characters for constructing distance Wagner networks. *Evolution* 38: 244–255.

Tostevin, G.B., 2003. A quest for antecedents: a comparison of the terminal Middle Palaeolithic and early Upper Palaeolithic of the Levant. In *More Than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East*, edited by A.N. Goring-Morris and A. Belfer-Cohen, pp. 54–67. Oxbow, Oxford.

Vaughan, C.D., 2001. A million years of style and function: regional and temporal variation in Acheulean handaxes. In *Style and Function: Conceptual Issues in Evolutionary Archaeology*, edited by T.D. Hurt and G.F.M. Rakita, pp. 141–163. Bergin & Garvey, Westport, CT.

von Cramon-Taubadel N. and Lycett, S.J., 2008. Human cranial variation fits iterative founder effect model with African origin. *American Journal of Physical Anthropology* 136: 108–113.

Whalen, N.M., Davis, W.P. and Pease, D.W., 1989. Early Pleistocene migrations into Saudi Arabia. *Atlal* 12: 59–75.

Whiten, A., 2005. The second inheritance system of chimpanzees and humans. *Nature* 437: 52–55.

Whiten, A., Goodall, J., McGrew, W.C., Nishida, T., Reynolds, V., Sugiyama, Y., Tutin, C.E.G., Wrangham, R.W. and Boesch, C., 1999. Cultures in chimpanzees. *Nature* 399: 682–685.

Whiten, A., Goodall, J., McGrew, W.C., Nishida, T., Reynolds, V., Sugiyama, Y., Tutin, C.E.G., Wrangham, R.W. and Boesch, C., 2001. Charting cultural variation in chimpanzees. *Behaviour* 138: 1481–1516.

Whiten, A., Horner, V., de Waal, F.B.M. 2005. Conformity to cultural norms of tool use in chimpanzees. *Nature* 437: 737–740.

Whiten, A., Spiteri, A., Horner, V., Bonnie, K.E., Lambeth, S.P., Schapiro, S.J. and de Waal, F.B.M., 2007. Transmission of multiple traditions within and between chimpanzee groups. *Current Biology* 17: 1038–1043.

Wright, S., 1931. Evolution in Mendelian populations. *Genetics* 16: 97–126.

Wynn, T. and Tierson, F., 1990. Regional comparison of the shapes of later Acheulean handaxes. American Anthropologist 92: 73–84.

Chapter 10
Comparing Stone Tool Resharpening Trajectories with the Aid of Elliptical Fourier Analysis

Radu Ioviţă

Abstract Resharpening has long played a confusing role in the history of research on lithic variability. In this chapter, I argue that, far from confounding issues of variability, resharpening can be used as a classificatory principle because it reflects human technical choices related to repeated uses of a tool. The advantage that resharpening offers is that of a mathematically suitable study object, through the investigation of shape change along the continuum of size reduction. Building upon a rich history of research in both biology and prehistoric archaeology, I present a variant of a new method for comparing resharpening trajectories, using elliptical Fourier analysis (EFA) and principal components analysis to compare the slopes of allometric regressions. The theoretical presentation is followed by a worked example using bifacial tools from two European Middle Paleolithic sites: Pech de l'Azé I (France) and Buhlen III (Germany).

Resharpening and the Resharpened Tool Concept

The importance of resharpening as a factor in determining lithic assemblage composition and variability has come to the forefront of research as late as the 1980s, despite the identification of the phenomena since the beginnings of lithic analysis (Holmes 1891, 1892). In the modern era, Americanists were the first to realize that lithic artifacts changed shape as they were resharpened and to account for some of the different shapes found in archaeological collections as "snapshots" of the same tool at different stages of its reduction (Ahler 1971; Frison 1968; Hoffman 1985). In Old World prehistory, despite pioneering studies of morphological modification in ethnographic stone tools (Cooper 1954), this idea took hold much later, beginning in the 1980s and 1990s, (Dibble 1984, 1987; Jelinek 1991; Kuhn 1991), and later being consolidated by research in other

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continents, (e.g., Australia, Hiscock and Attenbrow 2003), and other periods (e.g., the Acheulean, see McPherron 1995, 1999; North African Upper Paleolithic, Hiscock 1996).

In general, many parameters tied to reduction are explicable in simple economic terms, as a more or less direct result of raw material availability, distance, and quality (Blades 1999; inter alia, Rolland and Dibble 1990; Kuhn 1991; Shott 1989, 1995, 1996a). Besides the almost countless factors that affect tool reliability and rejuvenation *rates*, resharpening is essentially a continuous process by which the shape of the original object is altered in a generally stepwise fashion. Although blank shape as well as functional purpose of the tool probably determines its shape, it is rejuvenation or resharpening that accounts for the subsequent changes in shape. It is also clear that many kinds of Paleolithic tools were conceived partly with the intention, or at least with the foresight, of being maintained and resharpened. What has to be understood is that resharpening is not something that, regrettably, must happen to tools that had an otherwise specific morphology, to be subsequently altered through rejuvenation of the edges; it is rather an integral part of the tool itself, just like ageing is an integral part of living things. Thus, the shape of a tool does not go from the "real"/"original"/"desired" form to the "exhausted" one, but *it is* the collection of intermediary shapes that make up the tool itself. In other words, a tool can be defined as the *collection of all possible resharpening stages* it undergoes until it is abandoned.

So far, the majority of studies of tool reduction in the Paleolithic have focused on demonstrating that various artifact typologies were artificial discretizations of a continuum in morphological variation (e.g., Dibble 1984, 1987, 1995; Hiscock 1996; McPherron 1999). In that sense, their success can be considered a largely negative result, because it left behind an organizational vacuum. Typologies were originally devised as means of organizing "cultures" spatially and chronologically, and the blow dealt to this heuristic by reduction theories was heavy. Resharpening continuums were an added concern to already known problems, such as the imperfect correlation between individual artifact morphology and function, and the large number of economic factors affecting shape, resulting in a serious reduction of the archaeologist's ability to systematize cultural variability. However, a corollary of the reduction-continuum model of artifact variability is that, if *resharpening itself* is patterned, it could serve as a classificatory principle. Therefore, being able to compare resharpening continua with each other in a meaningful way is methodologically and conceptually usefulbecause resharpening is both behaviorally relevant (it indexes the activity that was performed with the tool) and ubiquitous (i.e., it applies to all "curated" tools, independent of production methods). Resharpening is also a direct consequence of function, i.e., how one uses a tool dictates which parts of it will be resharpened, and this is independent of the initial tool shape and size. Thus, incorporating the rejuvenation history of a tool into the concept of tool itself is both methodologically powerful, and at the same time behaviorally informative. In the rest of the paper, I will present some of the available methods for putting this concept in application, namely, for investigating patterns in resharpening trajectories, and for comparing resharpening trajectories in different classes of tools, using as an example bifacial tools from two industrial technocomplexes in the European Middle Paleolithic: the Mousterian of Acheulean Tradition and the Micoquian/Keilmessergruppen.

Describing "Types" of Resharpening

As I mentioned earlier, much of the work done to date on resharpening, especially by North American prehistorians, has been devoted to quantifying the *extent* and economic factors involved in reduction (Andrefsky Jr 2006; Clarkson 2002; Eren et al. 2005; Kuhn 1990; Shott 1995, 1996a, b, 1997; Shott and Sillitoe 2005; Shott and Weedman 2007). However, even though the realization that resharpening is patterned appears in the literature, systematizing types of resharpening has been a secondary concern. Hayden (1989) provided a classification of resharpening types in technological terms, i.e., soft vs. hard-hammer, grinding, etc., but the effects of these various techniques upon the geometric properties of the objects were not explicitly explored. With the exception of projectile points, where the re-working of broken pieces through resharpening has been the subject of systematic investigation, (Buchanan 2006; e.g., Flenniken and Raymond 1986), a formal connection between the kind of use and the kind of resharpening has been only sporadically made, although many writers working on the Old World Paleolithic have described resharpening patterns, especially through drawings of the transformations involved (Boëda 1995; Dibble 1995; Hiscock 1996; Jöris 2001; McPherron 1999; Richter 2004). Such a schematic depiction of three types of resharpening applied to the same tool is supplied in Fig. 10.1, with the intention of drawing attention to the shape changes that are to be expected from them. The first two patterns result in allometry (shape change), differing in function of symmetry, and the third type is isometric (shape-conserving). However, although such types of resharpening can be described and drawn schematically, it is advantageous from the point of view of both visualization and analysis to employ a more rigorous approach to shape analysis.

Sorting Out Shape and Size: A Short History of Research

Because resharpening produces shape change that is generally incremental (i.e., no stone-knapper wishes to lose half the material while rejuvenating a dull tool edge), it lends itself to quantification via the study of allometry. This is because, over time, tools are abandoned at various stages of reduction, allowing the archaeologist to reconstruct the intermediate steps going from the initial form (relatively large) to the exhausted one (relatively smaller). This change in shape can thus be quantified through a mathematical relationship between *shape* parameters and *size*, i.e., an *allometry* equation. Because size is a one-dimensional attribute, and can be expressed in a variety of ways (as weight or as a composite of metric measurements), the *kind* of allometry relationship that is relevant depends mostly on the type of shape quantification that is employed. Two major approaches to the mathematical description of shape exist: linear measurements and coordinate-based "geometric morphometrics," bringing with them a set of interrelated statistical techniques used to investigate allometry.

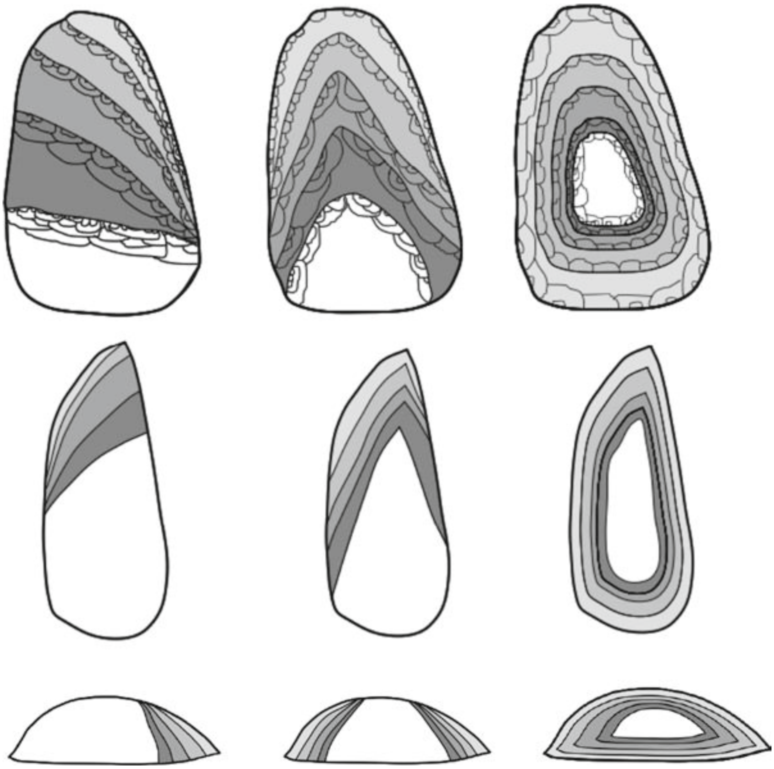

Fig. 10.1 Three types of resharpening reflecting functional and economic differences in tools of the same initial shape. Both the first and the second types are allometric (i.e., the shape changes with size), whereas the last type is largely isometric

In Paleolithic archaeology, the shape of artifacts has been traditionally quantified with the aid of linear caliper measurements, taken from recognizable landmarks such as bulbs of percussion, point tips, and so on. For instance, early sets of handaxe measurements, which included such attributes as "length", "width", "thickness", as well as several other measurements taken at intermediate points, were proposed by Alimen and Vignal (1952), Roe (1964; 1968), Cahen (1975), Isaac (1977), and Bordes (1979). Such measurements have the advantage of describing variables that are innately familiar to us. However, they are generally highly correlated with each other, and also describe form (shape + size) rather than simply shape. Therefore, ratios, such as "width to thickness," were often used to analyze shape trends.

The realization that shape and size were perhaps causally related featured very prominently in the debate about handaxe variability in the 1990s (Ashton and White 2003; McPherron 1995, 1999, 2000, 2003; White 1998; White and Pettitt 1995), with McPherron arguing that ovate and pointed handaxes were different ends of a spectrum spanned by size. Within this debate, Crompton and Gowlett (1993) were the first to explicitly use Jolicoeur's (1963) multivariate allometry.

The need for more precise descriptions of artifact shape began to be expressed starting in the 1970s with a number of studies aimed at bringing coordinate methods into archaeology, again, from the biological sciences. In the early 1970s, Montet-White (1973) introduced a system of polar coordinates for recording artifact shape, a system which was later popularized in a seminal study by Wynn and Tierson (1990). While such a characterization of an outline is also the basis for classical Fourier analysis, this technique was not employed until Gero and Mazzullo (1984) applied it to investigate variability in debitage outlines in two sets of stone tools. This study has had surprisingly little impact in the archaeological community, probably due to the difficulties associated with numerical methods on the day's computers.

Early attempts to quantify shape with the aid of Cartesian coordinates include Saragusti et al.'s (1998) introduction of continuous curvature measures, again with the aim of understanding symmetry in handaxes, followed up in a later article (Saragusti et al. 2005) where shape "roughness" is explored, also with the aid of Fourier coefficients. More recently, Nowell et al. (2003) used a technique called "deformation modeling" to examine some of the same questions. However, the first papers to use the classical geometric morphometrics (GM) framework (Bookstein 1989, 1991; Goodall 1991; Kendall 1984) were published in 2006 by Buchanan (2006) and Lycett et al. (2006). Buchanan examined the effect of distance to raw material on the allometric changes due to resharpening in Folsom projectile points. Buchanan's article established landmarks based on points along curves where linear measurements are usually taken (e.g., 1/3 of the length), along with three landmarks taken at the tip and the two base points. Lycett et al. used a specially designed 3D caliper to collect multiple semilandmarks on chopper-cores, polyhedral cores, and discoid cores from Soan (Siwalik, Pakistan) and handaxes from Attirampakkam (Tamil Nadu, India) and St. Acheul (France).

However, the adaptation of geometric morphometrics to the study of stone tools is far from complete. The vast majority of stone tools have no real homologous landmarks [Bookstein Type 1 (Bookstein 1991)], and, although methods that address this problem exist (e.g., Bookstein 1997; Gunz et al. 2005), their application to objects that have no Type 1 landmarks at all requires a great deal of caution. Another option in such cases is to focus on parameterizing whole curves (outlines), rather than configurations of points. The slow adoption of curve-based approaches into archaeology is partly due to their relative unpopularity with biologists (but see Sheets et al. 2006), who often have to relate curves to configurations of homologous landmarks, and therefore need to work within the Kendall shape-space framework. However, this difficulty does not apply to stone tools, where, as mentioned before, true Type 1 landmarks almost never exist. Therefore, outline methods are appropriate for stone tool analysis, and their use in the quantification of artifacts should be fully explored.

Fourier Methods

There are many parametric approaches to outline analysis, including polynomial approximations, classical Fourier analysis, eigenshape analysis, and, finally, elliptical Fourier analysis (EFA, Kuhl and Giardina 1982; Ferson et al. 1985). This technique,

an extension of the work of Jean-Baptiste Fourier (1768–1830), turns closed curves into linear combinations of sinusoidal (sine and cosine) functions with appropriate multiplicators (amplitudes).[1] The use of such Fourier approximations to quantify shape is not new and has been applied to a wide variety of problems, from hand print recognition (Granlund 1972) to the quantification of grain shape (Ehrlich and Weinberg 1970), and, most frequently, for the quantification of biological shapes (e.g., Cardini and Slice 2004; Daegling and Jungers 2000; Lestrel 1982; Friess and Baylac 2003; Lestrel and Brown 1976; Marchal 2000; Mitteroecker et al. 2004; Monti et al. 2001; Penin et al. 2002). The quality of the approximation can be arbitrarily good, at the expense of increasing the number of terms in the expansion, with each harmonic providing four extra terms. The balance between an accurate representation of the original data and the added complexity in the shape analysis is usually achieved by looking for an "elbow" or drop-off in benefit due to extra harmonics (see Fig. 10.2).

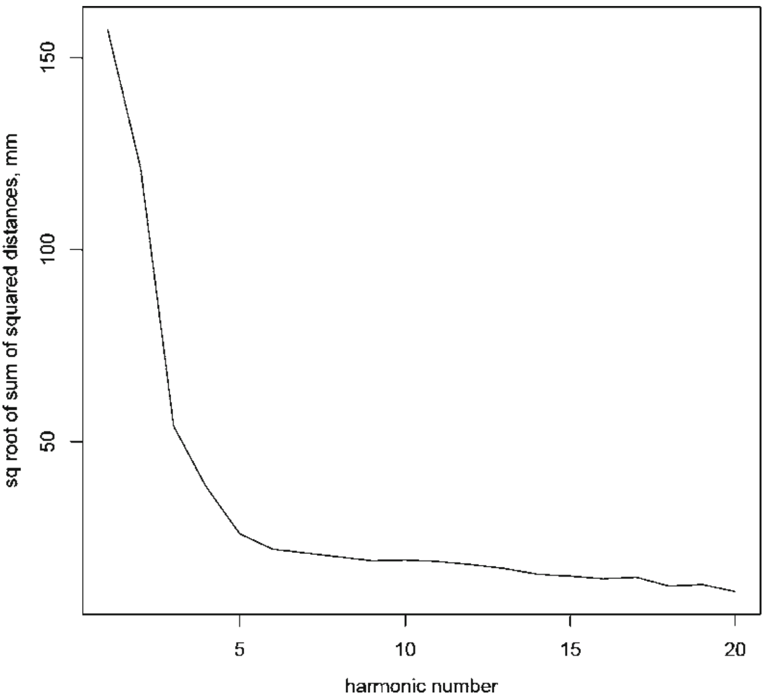

Fig. 10.2 The benefit of added harmonics to each approximations decreases. In this particular depiction, the first "elbow" can be seen at five harmonics. A visual inspection of the specimens along with such an assessment can be combined to decide on the necessary degree of accuracy

[1]The elliptical Fourier analysis (EFA) algorithm, invented by Kuhl and Giardina (1982), actually expresses the outline in terms of two functions representing incremental steps in the x and y directions, functions which are then subjected to Fourier analysis themselves.

In the case of the majority of stone tools, outline analysis can be carried out on digitized photographs taken at right angles, so as to take into account the holistic three-dimensional nature of the objects through the analysis of the cross-sections. The outlines are then translated and rotated to a standard position (with the centroid at (0,0)), and the Cartesian coordinates of each of the digitized points are divided by the outline area, so as to eliminate the effects of size. There are several roughly equivalent size-standardization methods (see the original paper by Kuhl and Giardina (1982) and the follow-up by Ferson et al. (1985) for some examples), and choosing between them is a matter of the kind of size measure that is desired. Several freely available computer software programs convert sets of coordinates (outlines) into elliptical Fourier coefficients, which can then be analyzed further.

Trajectories in Size-Shape Space

As mentioned before, a resharpening trajectory is simply the relationship between the geometric shape (size-free) and the size of stone tools. The investigation and comparison of resharpening trajectories in size-shape space can be done in a variety of ways. Because the shape information in geometric morphometric approaches is contained in a relatively large number of numerical variables (initially, Cartesian or polar coordinates of points, then in the form of Fourier coefficients, warp scores, etc.), and, consequently, a high dimensionality, it is difficult to visualize such trajectories directly in size-shape space. Therefore, a (usually linear) model of the relationship is first calculated, and then, the predictions are checked against the actual data.

Given a set of Fourier coefficients characterizing a size-free set of tools undergoing reduction through resharpening, the resharpening trajectory is nothing other than the relationship between the coefficients and size. This relationship can be expressed mathematically in a variety of ways, but one of the simplest and most convenient is through a multivariate multiple linear regression of shape on size (see Good (2005) and Iovita (2009) for further details on the method). The appropriateness of the regression equation for describing the relationship is then checked by a comparison of the shapes predicted by the regression with the actual shapes extracted from the objects themselves. The regression of shape on size results in a vector of coefficients, which describes the linear path of the trajectory through a multi-dimensional Euclidean space, whose dimension is determined by the number of harmonics (shape variables). Comparing trajectories is then performed by calculating the angles between the pairs of different vectors. The significance of the model must be checked using resampling methods because of the high likelihood that the data are not normally distributed. The advantage of using multivariate regression is that the entire shape data is retained, but the significance of the regression model is highly dependent on striking the right balance between a faithful approximation (a high number of harmonics) and the lowest possible dimensionality of the regression vectors (see Fig. 10.3).

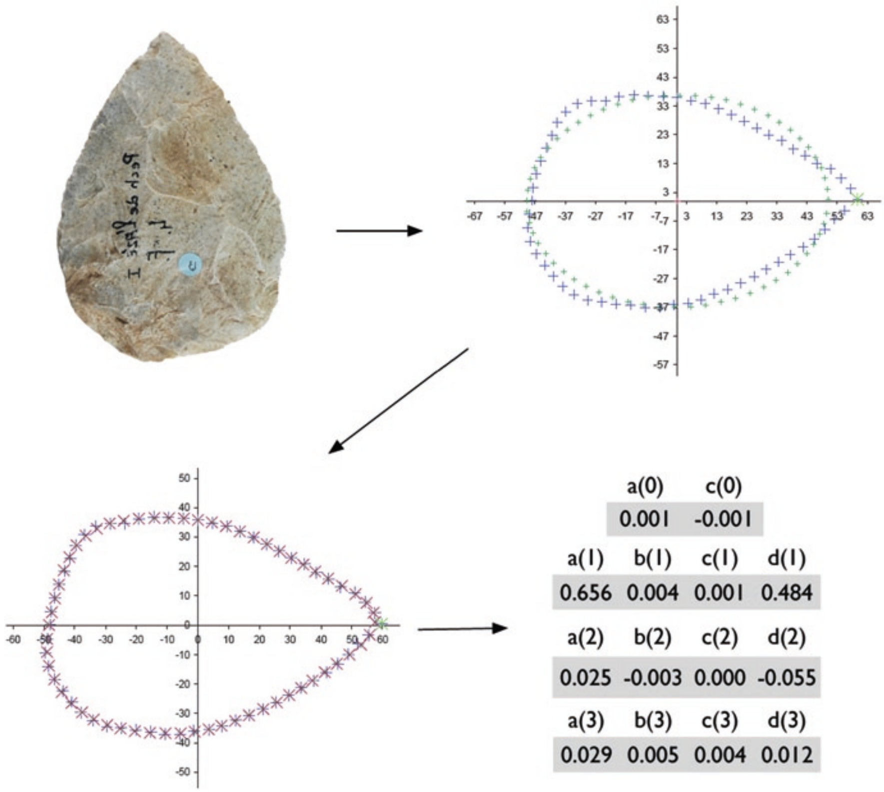

Fig. 10.3 From shape to Fourier coefficients: the digitized tool outline is converted into a set of equally spaced coordinate points, then increasing numbers of harmonics are used to obtain an increasingly better approximation of the outline. Finally, the EFA algorithm produces coefficients in the form presented here

A second possibility is to perform a Principal Components Analysis (PCA) on the EFA data, and to regress each individual coefficient on size (for an example using the same approach on landmarks, see Maddux and Franciscus 2009). Essentially, this reduces the data dimensionality further (ideally to within the first three components, accounting for the bulk of the variance) and allows us to examine projections of the trajectory on each of the principal component axes. The problem is, thus, reduced to a series of two-dimensional regression situations, and the slopes of the individual regressions can then be compared in the classical way, via a *t*-test, or, in the case of multiple samples, using ANOVA.

I have recently presented a detailed protocol for the comparison of resharpening trajectories using EFA and multivariate regression (Iovita 2009). In the next section, I will present an example of using EFA and PCA to investigate allometry in two assemblages of stone tools from the European Middle Paleolithic, namely from Pech de l’Azé I (France), and Buhlen III (Germany), which were also analyzed using the multivariate regression method mentioned above.

An Example

The material presented here comes from the sites of Pech de l'Azé I (layer 4) and Buhlen IIIb, both containing late Middle Paleolithic lithic assemblages, and representing respectively the Mousterian of Acheulean Tradition (MTA – Type A) (Bordes 1954) and the Micoquian or Keilmessergruppen industrial technocomplexes (Bosinski 1967). Both types of tools, the Keilmesser and MTA handaxe are form-shaped tools with a plano-convex cross section and more or less asymmetric cutting edge. Although the shapes themselves seem to be relatively different (see Figs. 10.4 and 10.5), and the production techniques are somewhat different (although both "bifacial"), a "knife"-like cutting function has been proposed for both of them (e.g., Soressi 2002; Jöris 2001, 2006).

In total 62 complete Keilmesser from Buhlen and 72 handaxes from Pech I were digitized from digital photographs using the free software tpsDig2 (Rohlf 2008), using 60 digitized points per outline and the tip as starting landmark. The artifacts were oriented with the tip facing right and the convex side toward the camera, and three photographs were taken at right angles, capturing the artifact from three orthogonal points of view.[2] A normalized Fourier transformation was applied using CartesianDiatom (Edgar 2007), such that the outline shapes are invariant with respect to starting point, size, and rotation, following the protocol of (Ferson et al. 1985), with the exception that here the outline area rather than the length of the

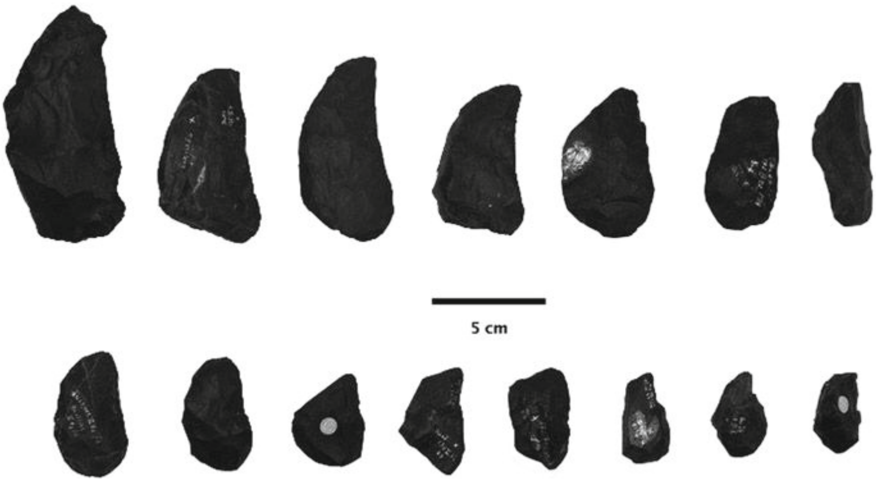

Fig. 10.4 Selected Keilmesser from Buhlen. Photographs by Radu Iovita, with permission of the Hessisches Landesmuseum Kassel

[2]See Iovita (2009) for further details related to the photographing setup, as well as the outline extraction and normalization.

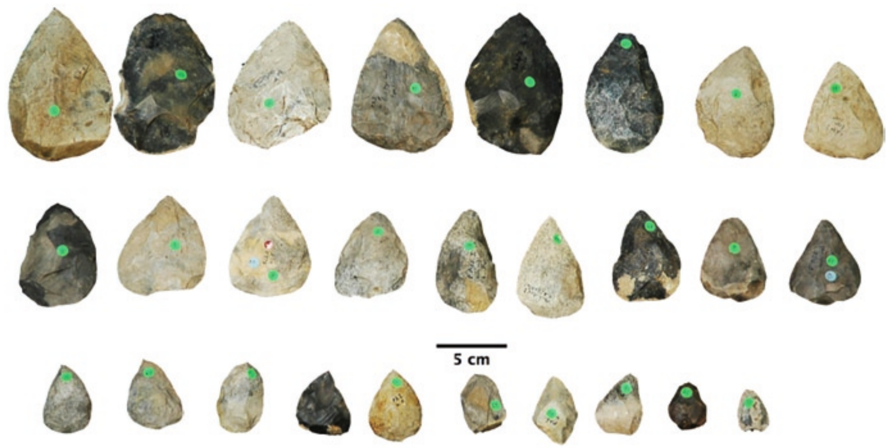

Fig. 10.5 Bifaces from layer 4 at Pech de l'Azé I. Photos by Radu Iovita, with the permission of the Musée National de Préhistoire, Les Eyzies-de-Tayac

semimajor axis of the best-fitting ellipse was used for size standardization. Under the normalization procedure, the first three coefficients of the first harmonic degenerate (i.e., are constant and should not be included in the analysis), and the fourth coefficient represents the width-to-length ratio of the first approximating ellipse.[3]

We shall be focusing on the top view of the tool, the view that is most commonly associated with the shapes of artifacts, but in practice, the same techniques can be applied to all three orthogonal sections or, indeed to any other two-dimensional section of interest. The data are first subjected to a PCA using the first nine harmonics. Because in some cases the majority of the shape information is captured by the first harmonic approximation, we will perform the analyses twice, the first time including the first harmonic (Fig. 10.6 and Tables 10.1 and 10.3), and the second time without it (see Fig. 10.7 and Tables 10.2 and 10.3).

When the first harmonic is included, the first nine PCs account for 95.3% of the variance, with the first three PCs totaling 74%. The next step is to calculate regression statistics for each of the first three PCs on size and evaluate the significance of the linear models. Table 10.1 shows that allometry in the PC1 is detected in the Buhlen sample, but not in any of the others, which mostly show complete isometry (no significant difference from a constant slope). The relationship is relatively weak, but nevertheless significant ($p < 0.01$), and, in order to visualize what is actually happening, we can plot the outlines that represent maximum and minimum values along the PC axes. This is done by first calculating a mean shape of the pooled samples, and adding the maximum and minimum PC scores multiplied by the relevant eigenvalues, and finally by using the inverse Fourier function to generate

[3]All subsequent analyses were conducted using the R statistical programming environment (RDevelopmentCoreTeam 2008).

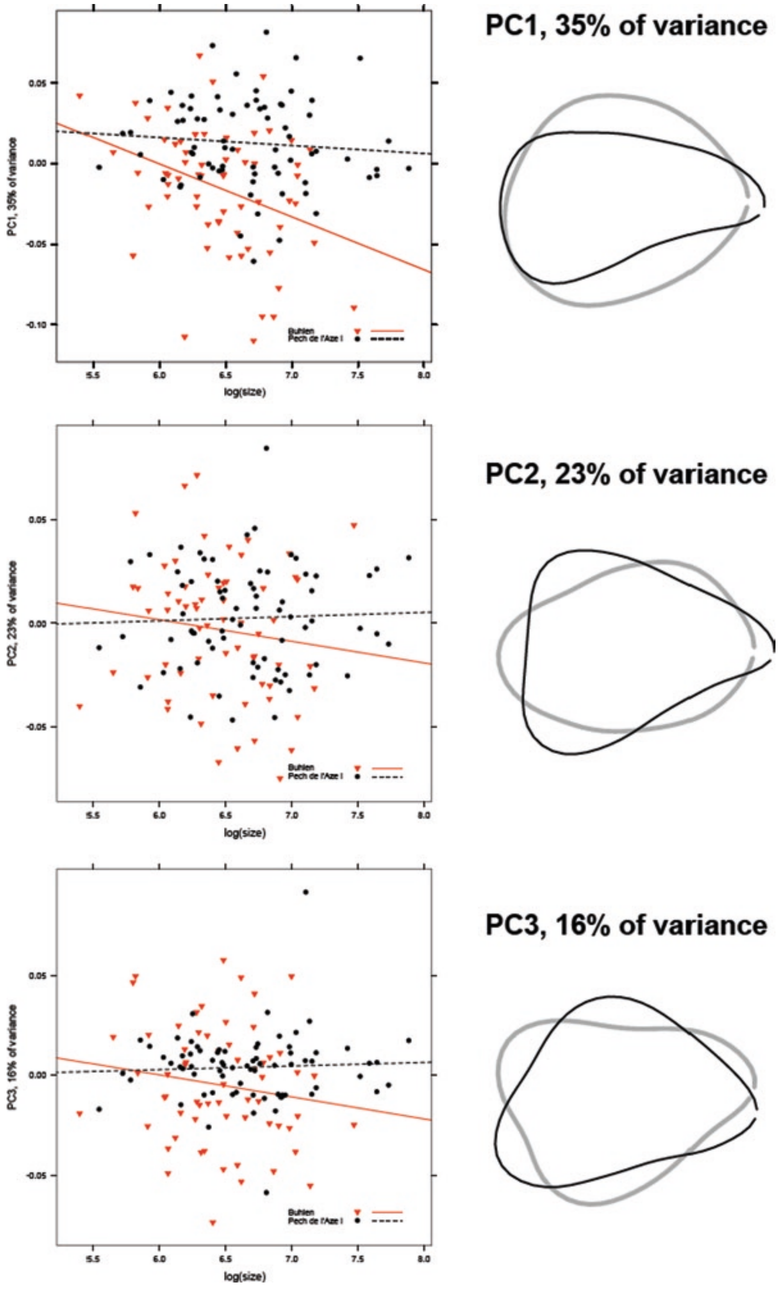

Fig. 10.6 Regressions of the first three principal components of the first nine harmonics on log(size). On the *right hand side* are plotted the shapes of the extreme values, with *black thin shapes* corresponding to the minimal values along the PC axes, and the *thick grey shapes* corresponding to the maximum values along the same PC axes

Table 10.1 Regressions of the first three principal components of the elliptical coefficients on log(size), first nine harmonics

		n	R^2	Adj R^2	Slope	*p*	*t*
PC1 vs. Size	Buhlen	62	0.12	0.11	–0.03	*<0.01*	*–2.87*
	Pech I	72	0.01	–0.01	0.01	0.46	–0.74
PC2 vs. Size	Buhlen	62	0.02	0.00	–0.01	0.32	–1.01
	Pech I	72	0.00	–0.01	0.00	0.74	0.33
PC3 vs. Size	Buhlen	62	0.02	0.01	–0.01	0.23	–1.21
	Pech I	72	0.00	–0.01	0.00	0.67	0.43

Table 10.2 Regressions of the first three principal components against log(size), harmonics 2–9

		n	R^2	Adj R^2	Slope	*p*	*t*
PC1 vs. Size	Buhlen	62	0.07	0.05	–0.02	*0.04*	*–2.10*
	Pech I	72	0.00	–0.01	0.00	0.96	0.05
PC2 vs. Size	Buhlen	62	0.02	0.00	–0.01	0.27	–1.11
	Pech I	72	0.00	–0.01	0.00	0.41	0.48
PC3 vs. Size	Buhlen	62	0.01	–0.01	–0.00	0.48	–0.71
	Pech I	72	0.00	–0.01	0.00	0.84	–0.19

Table 10.3 Differences between the slopes of the allometric regression of Buhlen and Pech de l'Aze I

Harmonics used in PCA	*t*-value PC1 vs. log(size)	*p*	*t*-value PC2 vs. log(size)	*p*	*t*-value PC3 vs. log(size)	*p*
1–9	*–2.10*	*0.04*	–1.04	0.30	–1.28	0.21
2–9	–1.78	0.07	–1.21	0.23	–0.55	0.58

new outlines.[4] Such a reconstruction of the extreme shapes indicates that, in the case of Buhlen, larger pieces are more elongated and more triangular, with the smaller pieces tending to a wider and more rounded shape, but which keeps the relative edge length asymmetry seen in the larger pieces. This is consistent with patterns of resharpening described by Jöris (2001) for Buhlen, and for Keilmesser in general, and which resemble patterns of scraper resharpening (see also Fig. 10.1, first or second hypothetical pattern). In contrast, Pech I does not exhibit any change in shape, although the variation in size is exactly the same as in Buhlen. Isometry in stone tool reduction must be seen as a result of knapper intention and could tentatively be explained as a result of either a desired tool shape (for functional purposes) or for double use as a more reliable core.

In order to tease out the remainder of the shape variation, we take the first harmonic out of the analysis. In this case, the first nine PCs account for 94% of the variance, and the first three describe now 70% of it. Although the difference in the amount explained

[4]The R code for the inverse Fourier transformation is from Claude (2008).

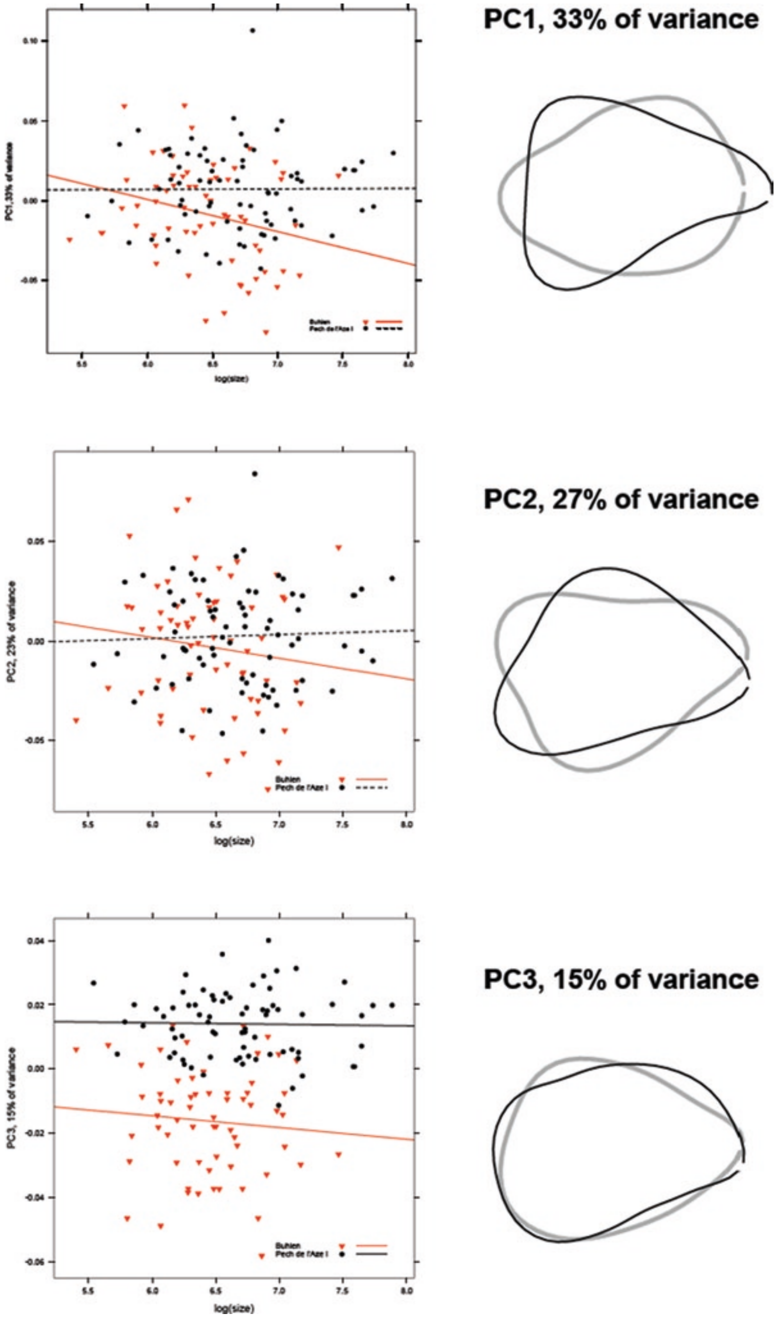

Fig. 10.7 Regressions of the first three principal components of the second through ninth harmonics on log(size). Note that the degree of allometry present in the Buhlen sample is somewhat reduced once the first harmonic is removed. On the *right hand side* are plotted the shapes of the extreme values, with *black thin shapes* corresponding to the minimal values along the PC axes, and the *thick grey shapes* corresponding to the maximum values along the same PC axes

by each of the first three PCs has not changed very much (see Fig. 10.7), the extreme shape reconstructions reveal that the new PC axes describe a different shape variation. Indeed, with the removal of the first harmonic, PC1 now seems to account for a shape change similar to that accounted for by PC2 in the previous analysis (see Fig. 10.6), that is, a difference between triangular and rounded shapes. Buhlen still retains a weak allometry with respect to PC1 (see Table 10.2, $p<0.05$), but not along any of the other PC axes, whereas Pech I exhibits isometry in all cases. PC3 seems to best distinguish the two samples (it is the only one where they do not overlap to a large degree), and the reconstructions confirm this, but neither of the regressions are significant.

Table 10.3 shows the pairwise comparisons of the regression slopes, none of which are significant except those related to PC1. However, the difference in slope between Buhlen and Pech I is still significant at the 0.05 level only when the first harmonic is retained, meaning that Buhlen is not significantly different from isometry (constant slope) unless the elongation of the pieces is taken into account. The differences in allometry exhibited by Buhlen and Pech I using this method match those discussed in a previous article using the multivariate regression method (Iovita 2009), and indicate that this is a robust pattern. The isometry of the Pech I handaxes described by both methods contradicts previous hypotheses of asymmetrical resharpening, possibly in a haft (e.g., Soressi 2002), and suggests that these tools may have served a purpose for which shape conservation was important.

Implications and Future Potential

I have argued for the importance of resharpening trajectories as an indicator of both tool function and economic behavior, and proposed the adoption of several methods from biology to deal with the quantitative aspects. The given example serves only the purpose of illustrating ways of manipulating outline data for investigating questions about shape change in stone tools. However, the proposed technique for quantifying resharpening trajectories has ramifying implications for studies of tool function, and, consequently, for typology and assemblage classification. Of special interest are studies of prehension and hafting, which concern the preferential or partial reduction of the active edges of stone tools as they are used. These resharpening patterns lend themselves to study because they necessarily generate studiable allometries.

More generally, within the domain of systematics, studies of tool diversity within a technocomplex or a period, such as the Middle Paleolithic of Europe or the African Middle Stone Age, a topic which has been gaining increasing importance for intercontinental comparisons in particular (Brooks et al. 2006; McBrearty and Brooks 2000; Mellars 2002; Mellars and Grün 1991), can benefit from a rigorous approach to morphology and resharpening. This and similar methodologies may help to shift the focus of typology away from the formal aspects of tool shape to those of the behavioral aspects of tool maintenance and purpose.

Finally, this type of research into the definition and study of formal tool modification can serve as a valuable complement to studies of production techniques, such as those offered by the *chaîne opératoire* school. More specifically, hypotheses related to reduction processes, which can originate in descriptions of various operational sequences of production can be tested using similar models of shape change as are proposed here.

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References

Ahler, S., 1971. *Projectile Point Form and Function at Rodgers Shelter, Missouri*. Missouri Archaeological Society Research Series no. 8, University of Missouri, Columbia.

Alimen, H. and Vignal, A., 1952. Etude statistique de biface acheuleens. Essai d'archeometrie. *Bulletin de la Société Préhistorique Française* 49: 56–72.

Andrefsky, W., 2006. Experimental and archaeological verification of an index of retouch for hafted bifaces. *American antiquity* 71: 743–757.

Ashton, N. and White, M., 2003. Bifaces and raw materials: flexible flaking in the British Early Paleolithic. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H.L. Dibble, pp. 109–124. University Museum Monographs. University of Pennsylvania Press, Philadelphia.

Blades, B.S., 1999. Aurignacian lithic economy and early modern human mobility: new perspectives from classic sites in the Vezere valley of France. *Journal of Human Evolution* 37: 91–120.

Boëda, E., 1995. Steinartefakt-Produktionssequenzen im Micoquien der Kulna-Höhle. *Quartär* 45: 75–98.

Bookstein, F.L., 1989. Principal warps: thin-plate splines and the decomposition of deformations. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 11: 567–585.

Bookstein, F.L., 1991. *Morphometric Tools for Landmark Data: Geometry and Biology*. Cambridge University Press, Cambridge.

Bookstein, F.L., 1997. Landmark methods for forms without landmarks: morphometrics of group differences in outline shape. *Medical Image Analysis* 1: 225–243.

Bordes, F., 1954. Les gisements du Pech de l'Azé (Dordogne). I. Le Moustérien de tradition acheuléenne (avec une note paléontologique de J. Bouchoud). *L'Anthropologie* 58: 401–432.

Bordes, F., 1979, *Typologie du Paléolithique Ancien et Moyen.* Cahiers du Quaternaire 1. C.N.R.S., Bordeaux.

Bosinski, G., 1967. *Die mittelpaläolithischen Funde im westlichen Mitteleuropa*. Fundamenta Böhlau-Verlag, Köln and Graz.

Brooks, A.S., Nevell, L., Yellen, J.E. and Hartman, G., 2006. Projectile technologies of the African MSA: implications for modern human origins. In *Transitions Before the Transition: Evolution and Stability in the Middle Paleolithic and Middle Stone Age*, edited by E. Hovers and S.L. Kuhn, pp. 233–255. Springer, Netherlands.

Buchanan, B., 2006. An analysis of Folsom projectile point resharpening using quantitative comparisons of form and allometry. *Journal of Archaeological Science* 33: 185–199.

Cahen, D., 1975. *Le site archéologique de La Kamoa (Région du Shaba, République du Zaire), de l'Age de la Pierre Ancienne à l'Age du Fer*. Annales, Serie in 8c, Sciences Humaines 84. Musée Royal de l'Afrique Centrale, Tervuren.

Cardini, A. and Slice, D.E., 2004. Mandibular shape in the genus Marmota (Rodentia, Sciuridae): a preliminary analysis using outlines. *Italian Journal of Zoology* 71: 17–25.

Clarkson, C., 2002. An index of invasiveness for the measurement of unifacial and bifacial retouch: a theoretical, experimental and archaeological verification. *Journal of Archaeological Science* 29: 65–75.

Claude, J., 2008. *Morphometrics with R*. Use R. Springer, New York.

Cooper, H.M., 1954. Material culture of Australian Aborigines Part 1. Progressive modification of a stone artefact. *Records of the Australian Museum* 11: 91–97.

Crompton, R.H. and Gowlett, J.A.J., 1993. Allometry and multidimensional form in Acheulean bifaces from Kilombe, Kenya. *Journal of Human Evolution* 25: 175–199.

Daegling, D.J. and Jungers, W.L., 2000. Elliptical Fourier analysis of symphyseal shape in great ape mandibles. *Journal of Human Evolution* 39: 107–122.

Dibble, H.L., 1984. Interpreting typological variation of Middle Paleolithic scrapers: function, style, or sequence of reduction? *Journal of Field Archaeology* 11: 431–436.

Dibble, H.L., 1987. The interpretation of Middle Palaeolithic scraper morphology. *American Antiquity* 52: 109–117.

Dibble, H.L., 1995. Middle Paleolithic scraper reduction: background, clarification, and review of evidence to data. *Journal of Archaeological Method and Theory* 2: 299–368.

Edgar, R.K., 2007. CartesianDiatom-EFA: software for Elliptical Fourier Analysis. Version 1.1. www.diatom.org.

Ehrlich, R. and Weinberg, B., 1970. An exact method for characterization of grain shape. *Journal of Sedimentary Petrology* 40: 205–212.

Eren, M.I., Domínguez-Rodrigo, M., Kuhn, S.L., Adler, D.S., Le, I. and Bar-Yosef, O., 2005. Defining and measuring reduction in unifacial stone tools. *Journal of Archaeological Science* 32: 1190–1201.

Ferson, S., Rohlf, F.J., and Koehn, R.K., 1985. Measuring shape variation of two-dimensional outlines. *Systematic Zoology* 34: 59–68.

Flenniken, J.J. and Raymond, A.W., 1986. Morphological projectile point typology: replication, experimentation, and technological analysis. *American Antiquity* 51: 603–614.

Friess, M. and Baylac, M., 2003. Exploring artificial cranial deformation using elliptic Fourier analysis of Procrustes aligned outlines. *American Journal of Physical Anthropology* 122: 11–22.

Frison, G.C., 1968. A functional analysis of certain chipped stone tools. *American Antiquity* 33: 149–155.

Gero, J.M. and Mazzullo, J., 1984. Analysis of artifact shape using Fourier series in closed form. *Journal of Field Archaeology* 11: 315–322.

Good, P.I., 2005. *Introduction to Statistics Through Resampling Methods and R/S-PLUS*. Wiley-Interscience, New York.

Goodall, C., 1991. Procrustes methods in the statistical analysis of shape. *Journal of the Royal Statistical Society. Series B* 53: 285–339.

Granlund, G.H., 1972. Fourier preprocessing for hand print character recognition. *IEEE Trans Comput* C-21: 195–201.

Gunz, P., Mitteroecker, P. and Bookstein, F.L., 2005. Semilandmarks in three dimensions. In *Modern Morphometrics in Physical Anthropology*, edited by D.E. Slice, pp. 73–98. Springer-Verlag, New York.

Hayden, B., 1989. From chopper to celt: the evolution of resharpening techniques. In *Time, Energy and Stone Tools*, edited by R. Torrence, pp. 7–16. Cambridge University Press, Cambridge.

Hiscock, P., 1996. Transformations of Upper Palaeolithic implements in the Dabba industry from Haua Fteah (Libya). *Antiquity* 70: 657–664.

Hiscock, P. and Attenbrow, V., 2003. Early Australian implement variation: a reduction model. *Journal of Archaeological Science* 30: 239–249.

Hoffman, C., 1985. Projectile point maintenance and typology: assessment with factor analysis and canonical correlation. In *For Concordance in Archaeological Analysis: Bridging Data Structure, Quantitative Technique, and Theory*, edited by C. Carr, pp. 566–612. Wesport Press, Kansas City, MO.

Holmes, W.H., 1891. Manufacture of stone arrow points. *American Anthropologist* 4: 49–58.

Holmes, W.H., 1892. Modern quarry refuse and the Paleolithic theory. *Science* 20: 295–297.

Iovita, R.P., 2009. Ontogenetic scaling and lithic systematics: method and application. *Journal of Archaeological Science* 36: 1447–1457.

Isaac, G.L., 1977. *Olorgesailie. Archaeological Studies of a Middle Pleistocene Lake Basin in Kenya*. University of Chicago Press, Chicago.

Jelinek, A.J., 1991. Observations on reduction patterns and raw materials in some Middle Paleolithic industries in the Perigord. In *Raw Material Economies Among Prehistoric Hunter-Gatherers*, edited by A. Montet-White and S. Holen, pp. 7–32. University of Kansas Publication in Anthropology, 19. University of Kansas, Lawrence.

Jolicoeur, P., 1963. The multivariate generalization of the allometry equation. *Biometrics* 19: 497–499.

Jöris, O., 2001. *Der spätmittelpaläolithische Fundplatz Buhlen (Grabungen 1966-69). Stratigraphie, Steinartefakte und Fauna des Oberen Fundplatzes*. Universitätsforsch. Prähist. Arch. 73. Bonn.

Jöris, O., 2006. Bifacially Backed Knives (Keilmesser) in the Central European Middle Palaeolithic. In *Axe-Age: Acheulian Tool-Making from Quarry to Discard*, edited by N. Goren-Inbar and G. Sharon, pp. 287–310. Equinox, London; Oakville, CT.

Kendall, D.G., 1984. Shape-manifolds, Procrustean metrics, and complex projective spaces. *Bulletin of the London Mathematical Society* 16: 81–121.

Kuhl, F.P. and Giardina, C.R., 1982. Elliptic Fourier features of a closed contour. *Computer Graphics and Image Processing* 18: 236–258.

Kuhn, S.L., 1990. Geometric index of reduction for unifacial stone tools. *Journal of Archaeological Science* 17: 583–593.

Kuhn, S.L., 1991. "Unpacking" reduction: lithic raw material economy in the Mousterian of west-central Italy. *Journal of Anthropological Archaeology* 10: 76–106.

Lestrel, P.E., 1982. A Fourier analytic procedure to describe complex morphological shapes. *Progress in Clinical and Biological Research* 101: 393–409.

Lestrel, P.E. and Brown, H.D., 1976. Fourier analysis of adolescent growth of the cranial vault: a longitudinal study. *Human Biology* 48: 517–528.

Lycett, S.J., von Cramon-Taubadel, N. and Foley, R.A., 2006. A crossbeam co-ordinate caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. *Journal of Archaeological Science* 33: 847–861.

Maddux, S.D. and Franciscus, R.G., 2009. Allometric scaling of infraorbital surface topography in *Homo*. *Journal of Human Evolution* 56: 161–174.

Marchal, F., 2000. A new morphometric analysis of the hominid pelvic bone. *Journal of Human Evolution* 38: 347–365.

McBrearty, S. and Brooks, A.S., 2000. The revolution that wasn't: a new interpretation of the origin of modern human behavior. *Journal of Human Evolution* 39: 453–563.

McPherron, S.P., 1995. A re-examination of the British biface data. *Lithics* 16: 47–63.

McPherron, S.P., 1999. Ovate and pointed handaxe assemblages: two points make a line. *Préhistoire Européenne* 14: 9–32.

McPherron, S.P., 2000. Handaxes as a measure of the mental capabilities of early hominids. *Journal of Archaeological Science* 27: 655–663.

McPherron, S.P., 2003. Technological and typological variability in the bifaces from Tabun Cave, Israel. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H.L. Dibble, pp. 55–75. University Museum Monographs. University of Pennsylvania Museum of Archaeology and Anthropology Publications, Philadelphia.

Mellars, P.A., 2002. Archaeology and the origins of modern humans: European and African perspectives. In *The Speciation of Modern Homo sapiens*, edited by T.J. Crow, pp. 31–48. Proceedings of the British Academy. The British Academy, London.

Mellars, P.A. and Grün, R., 1991. A comparison of the Electron Spin Resonance and thermoluminescence dating methods: the results of ESR dating at Le Moustier (France). *Cambridge Archaeological Journal* 1: 269–276.

Mitteroecker, P., Gunz, P., Bernhard, M., Schaefer, K. and Bookstein, F.L., 2004. Comparison of cranial ontogenetic trajectories among great apes and humans. *Journal of Human Evolution* 46: 679–697.

Montet-White, A. 1973. *Le Malpas Rockshelter: A Study of Late Paleolithic Technology in Its Environmental Setting.* Publications in anthropology 4. University of Kansas, Lawrence.

Monti, L., Baylac, M. and Lalanne-Cassou, B., 2001. Elliptic Fourier analysis of the form of genitalia in two Spodoptera species and their hybrids (Lepidoptera: Noctuidae). *Biological Journal of the Linnean Society* 72: 391–400.

Nowell, A., Park, K., Metaxas, D. and Park, J., 2003. Deformation modeling: a methodology for analyzing handaxe morphology and variability. In *Multiple Approaches to the Study of Bifacial Technologies*, edited by M. Soressi and H.L. Dibble, pp. 193–208. University of Pennsylvania Museum of Archaeology and Anthropology Publications, Philadelphia.

Penin, X., Berge, C. and Baylac, M., 2002. Ontogenetic study of the skull in modern humans and the common chimpanzees: neotenic hypothesis reconsidered with a tridimensional Procrustes analysis. *American Journal of Physical Anthropology* 118: 50–62.

RDevelopmentCoreTeam, 2008. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Richter, J., 2004. Copies of flakes: operational sequences of foliate pieces from Buran-Kaya III level B1. In *The Middle Paleolithic and Early Upper Paleolithic of Eastern Crimea*, edited by V. Chabai, K. Monigal, and A.E. Marks, pp. 233–248. ERAUL, Liège

Roe, D.A., 1964. The British Lower and Middle Palaeolithic: some problems, methods of study, and preliminary results. *Proceedings of the Prehistoric Society* 30: 245–267.

Roe, D.A., 1968. British Lower and Middle Palaeolithic handaxe groups. *Proceedings of the Prehistoric Society* 34: 1–82.

Rohlf, F.J., 2008. tpsDig2. Version 2.12, http://life.bio.sunysb.edu/morph/morphmet/tpsdig2w32.exe.

Rolland, N. and Dibble, H.L., 1990. A new synthesis of Middle Paleolithic assemblage variability. *American Antiquity* 55: 480–499.

Saragusti, I., Karasik, A., Sharon, I. and Smilansky, U., 2005. Quantitative analysis of shape attributes based on contours and section profiles in artifact analysis. *Journal of Archaeological Science* 23: 841–853.

Saragusti, I., Sharon, I., Katzenelson, O., Avnir, D., 1998. Quantitative analysis of the symmetry of artefacts: Lower Paleolithic handaxes. *Journal of Archaeological Science* 25: 817–825.

Sheets, H. D., Covino, K., Panasiewicz, J., Morris, S., 2006. Comparison of geometric morphometric outline methods in the discrimination of age-related differences in feather shape. *Frontiers in Zoology* 3: 15.

Shott, M.J., 1989. On tool-class use lives and the formation of archaeological assemblages. *American Antiquity* 54: 9–30.

Shott, M.J., 1995. How much is a scraper? Curation, use rates, and the formation of scraper assemblages. *Lithic Technology* 20: 53–72.

Shott, M.J., 1996a. An exegesis of the curation concept. *Journal of Anthropological Research* 52: 259–280.

Shott, M.J., 1996b. Stage versus continuum in the debris assemblage from production of a fluted biface. *Lithic Technology* 21: 6–22.

Shott, M., 1997. Stones and shafts redux: the metric discrimination of chipped-stone dart and arrow points. *American Antiquity* 62: 86–101.

Shott, M. and Sillitoe, P., 2005. Use life and curation in New Guinea experimental used flakes. *Journal of Archaeological Science* 32: 653–663.

Shott, M.J. and Weedman, K.J., 2007. Measuring reduction in stone tools: an ethnoarchaeological study of Gamo hidescrapers from Ethiopia. *Journal of Archaeological Science* 34: 1016–1035.

Soressi, M., 2002. *Le Moustérien de tradition acheuléenne du sud-ouest de la France. Discussion sur la signification du faciès à partir de l'étude comparée de quatre sites: Pech-de-l'Azé I, Le Moustier, La Rochette et la Grotte XVI*. unpublished PhD dissertation, Université de Bordeaux I,

White, M.J., 1998. On the significance of Acheulean biface variability in Southern Britain. *Proceedings of the Prehistoric Society* 66: 1–28.

White, M.J. and Pettitt, P.B., 1995. Technology of early Palaeolithic Western Europe: an heuristic framework. *Lithics* 16: 27–40.

Wynn, T. and Tierson, F., 1990. Regional comparison of the shapes of later Acheulean handaxes. *American Anthropologist* 92: 73–84.

Chapter 11
An Assessment of the Impact of Resharpening on Paleoindian Projectile Point Blade Shape Using Geometric Morphometric Techniques

Briggs Buchanan and Mark Collard

Abstract Paleoindian archaeologists have long recognized that resharpening has the potential to affect the shape of projectile points. So far, however, the impact of resharpening on the distinctiveness of the blades of Paleoindian projectile points has not been investigated quantitatively. With this in mind, we used geometric morphometric techniques to compare the blades of Clovis, Folsom, and Plainview projectile points from the Southern Plains of North America. We evaluated two hypotheses. The first was that blade shape distinguishes the three types. We found that blade shape distinguished Clovis points from both Folsom and Plainview points, but did not distinguish Folsom points from Plainview points. The second hypothesis we tested was that resharpening eliminates blade shape differences among the types. To test this hypothesis, we used size as a proxy for resharpening. The results of this analysis were similar to those obtained in the first analysis. Thus, our study suggests that, contrary to what is often assumed, resharpening does not automatically undermine the use of blade shape in Paleoindian projectile point typologies.

Introduction

The assignment of projectile points to types is critical for research on the Paleoindian period in North America. Paleoindian specialists rely on projectile point typology to situate assemblages in time when directly dateable material is not recovered. Furthermore, because Paleoindian points are found in such high numbers in mixed or isolated surface contexts, many studies concerning changes in technology and land use have relied on typed specimens (e.g., Anderson and Faught 2000).

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Paleoindian projectile point types are identified in part by characters that describe blade shape (Bamforth 1991; Bradley and Stanford 1987; Morrow and Morrow 1999). However, the use of such characters for classification purposes has been called into question by Flenniken and Raymond (1986). Drawing on the results of a replication study, these authors claim that resharpening has the potential to alter projectile point blade shape in such a way that blade shape no longer distinguishes between types. Clearly, if Flenniken and Raymond (1986) are correct, blade shape should be removed from the list of characteristics used to classify Paleoindian projectile points. This would be particularly problematic because some of the other characters that are considered to be diagnostic for certain Paleoindian projectile point types (e.g., presence/absence of a channel flake) do not occur on all specimens.

Paleoindian archaeologists have long recognized that resharpening has the potential to affect the shape of projectile points (Ellis 2004; Haynes 1980; Hofman 1991, 1992; Shott and Ballenger 2007; Wheat 1976, 1977). So far, however, the impact of resharpening on the distinctiveness of the blades of Paleoindian projectile points has not been investigated quantitatively. With this in mind, we carried out a study in which we used geometric morphometric techniques to evaluate the conventional hypothesis that blade shape distinguishes Paleoindian projectile point types, and also Flenniken and Raymond's (1986) claim that resharpening eliminates blade shape differences among projectile point types. The projectile points we examined are from the Southern Plains of North America and have been assigned to three important Paleoindian types – Clovis, Folsom, and Plainview.

Materials and Methods

Materials

The Southern Plains consists of the Southern High Plains and the Rolling Plains (Fig. 11.1). The Southern High Plains form an almost featureless plateau covering over 130,000 km^2 of western Texas and eastern New Mexico (Holliday 1995). Also known as the Osage Plains, the Rolling Plains are more topographically variable than the Southern High Plains. They lie to the east of the latter, and cover west-central Missouri, southeastern Kansas, and most of central Oklahoma. They also extend into north-central Texas. We focused on points from a single physiographic region in an effort to control for the potentially confounding impact of cultural selection in relation to environmental conditions. We reasoned that such selection is less likely to be a problem when comparing points from one physiographic region than when comparing points from several, since environmental differences are greater between physiographic regions than within them (Cannon 2004; Hunt 1967). We chose the Southern plains because it has a particularly rich archaeological record for the Paleoindian period (Buchanan 2006; Buchanan et al. 2007; Holliday 1997).

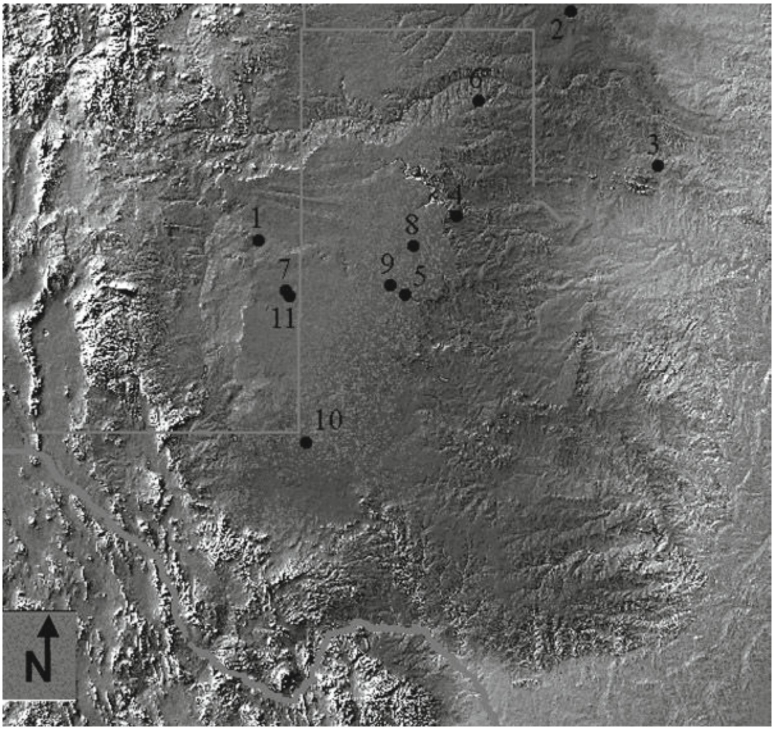

Fig. 11.1 Orthophotograph of the Southern Plains including portions of western Oklahoma, west Texas, and eastern New Mexico showing the locations of assemblages in the analysis. Site names: 1=Blackwater Draw, 2=Cooper, 3=Domebo, 4=Lake Theo, 5=Lubbock Lake, 6=Miami, 7=Milnesand, 8=Plainview, 9=Ryan's, 10=Shifting Sands, and 11=Ted Williamson

The sample comprised 28 Clovis points, 47 Folsom points, and 111 Plainview points (Table 11.1). Clovis points are lanceolate in outline with a straight to slightly concave base (Haynes 2002; Hester 1972; Howard 1990). They also usually have a so-called "channel flake" removal. A channel flake is a short (usually less than half the length of the face) flake detached perpendicular to the base. The available evidence suggests that Clovis points were used by populations across North America to hunt large game, including mammoth and bison (Haynes 2002). Folsom points also have lanceolate-shaped blades (Crabtree 1966; Meltzer 2006). They differ from Clovis points in having markedly indented bases and "flutes." The latter are flakes that are removed from the base usually up to two-thirds the length of a point. Folsom points are mostly restricted to the Great Plains and Rocky Mountain regions of western North America, where they appear to have been primarily used to hunt bison. Plainview points are unfluted lanceolate forms. The populations that made Plainview points on the Southern Plains are also thought to have been specialized bison hunters (Sellards et al. 1947). Clovis, Folsom, and Plainview are widely considered to represent a chronological sequence in the Southern Plains (e.g., Holliday 2000;

Table 11.1 The number of projectile points from each assemblage by the type used in the analysis

Site/assemblage	Type	Number of points	References
Blackwater draw	Clovis	22	Boldurian and Cotter (1999); Cotter (1937, 1938); Hester (1972); Howard (1935); Warnica (1966)
Domebo	Clovis	3	Leonhardy (1966)
Miami	Clovis	3	Holliday et al. (1994); Sellards (1938, 1952)
Blackwater Draw-Mitchell Locality	Folsom	2	Boldurian (1990)
Blackwater Draw	Folsom	12	Boldurian and Cotter (1999); Hester (1972)
Cooper	Folsom	10	Bement (1999a, b)
Lake Theo	Folsom	3	Buchanan (2002); Harrison and Killen (1978); Harrison and Smith (1975)
Lubbock Lake	Folsom	6	Johnson (1987)
Shifting Sands	Folsom	14	Amick et al. (1989); Hofman et al. (1990)
Milnesand	Plainview	39	Sellards (1955); Warnica and Williamson (1968)
Plainview	Plainview	10	Holliday (1997); Johnson et al. (1986); Knudson (1983); Sellards et al. (1947); Speer (1983)
Ryan's	Plainview	11	Hartwell (1995)
Ted Williamson	Plainview	51	Buchanan et al. (1996); Johnson et al. (1986); Warnica and Williamson (1968)

Taylor et al. 1996). Clovis is thought to be the oldest of the three types (ca. 13,340–12,830 calendar years ago). According to the conventional chronology, Folsom follows Clovis in time (ca. 12,830–11,900 calendar years ago). The dating of Plainview is uncertain, but generally is thought to overlap with Folsom on the younger end of the latter's time range (Holliday 2000; Holliday et al. 1999).

In order to analyze the full range of variability associated with each point type, only points from assemblages recovered from unmixed contexts were included in the sample. Incorporating isolated points found on the surface would have increased the size of our sample, but it also would have likely biased our results. The reason for this is that isolated points that have been assigned to a type are necessarily distinctive regardless of the amount of resharpening. Thus, including such points would have increased the likelihood of our analyses supporting the conventional hypothesis.

The points come from 13 assemblages recovered from 11 sites. Ten of the assemblages are from the Southern High Plains and three from the Rolling Plains. The Clovis assemblages are associated with mammoth kills (Blackwater Draw, Domebo,

and Miami). Some of the Folsom assemblages were recovered from campsites (Blackwater Draw-Mitchell Locality and Shifting Sands). Others were recovered from bison butchering locales (Blackwater Draw, Cooper, Lake Theo, and Lubbock Lake). The Plainview assemblages are from a campsite (Ted Williamson), two bison butchering sites (Milnesand and Plainview), and a cache (Ryan's).

We have used a number of the points in previous studies (Buchanan 2006; Buchanan et al. 2007; Buchanan and Collard 2007). The samples of Folsom and Plainview points used in this study differ from the samples used by Buchanan (2006) and Buchanan et al. (2007). Buchanan (2006) focused on Folsom points from the Southern Plains made only of Edwards chert in order to measure the shape change with distance from source. This restriction was removed in the present study and seven points made of raw materials other than Edwards chert were added to the sample. Seven Folsom points used by Buchanan (2006) were excluded from the study reported here because they were insufficiently complete. Buchanan et al. (2007) also employed a number of incomplete specimens in their analysis of Plainview points. These specimens were also not included in the study reported here. Lastly, we excluded points from three Plainview assemblages that Buchanan et al. (2007) concluded are problematic – Blackwater Draw, Warnica–Wilson, and Lubbock Lake FA5-17. The Blackwater Draw assemblage appears to be from a mixed context. The Warnica–Wilson assemblage comprises material from a campsite combined with a surface collection of points from the surrounding county. The Lubbock Lake FA5-17 assemblage was excluded because the points it contains likely represent a unique type.

Methods

Geometric morphometrics is a suite of methods for acquiring, processing, and analyzing Cartesian coordinate data (Bookstein 1991; Rohlf and Marcus 1993; Slice 2005; Zelditch et al. 2004). The core of geometric morphometrics is the separation of shape from size. This is accomplished by removing differences due to location, scale, and rotational effects. The geometric information that remains after these differences are eliminated is defined as shape.

The steps taken in the acquisition, processing, and extraction of projectile blade shape variables are as follows.

1. *Image acquisition*. Digital images of projectile points were used to capture landmark data. Projectile points were laid flat with their distal ends facing to the right in each photograph (Fig. 11.2). For nearly flat objects, such as projectile points, a two-dimensional approach produces limited information loss (Velhagen and Roth 1997).
2. *Choice and digitization of landmarks*. There are three locations on Paleoindian points that can serve as type II landmarks. A type II landmark is a landmark described by geometric evidence such as the minimum or maximum positions

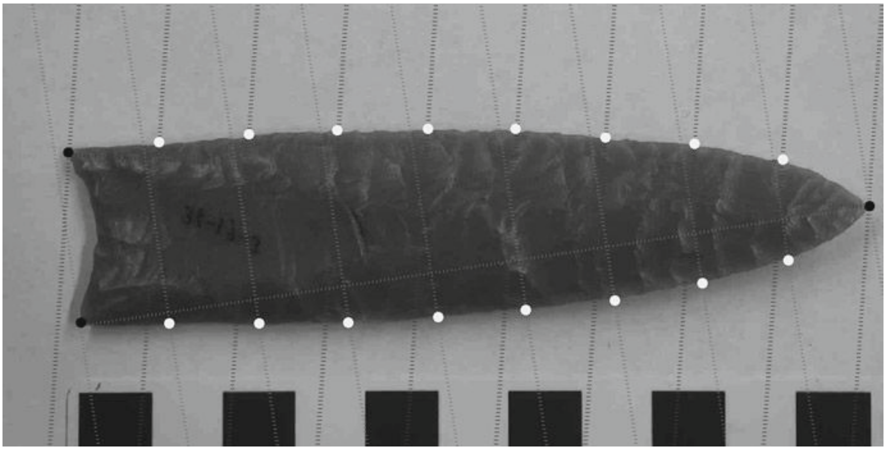

Fig. 11.2 Digital image of a projectile point with the locations of three homologous landmarks (*black circles*) and 16 pseudolandmarks (*white circles*) marked on the projectile point. The lines superimposed on the point image were produced using the MakeFan program

along a curve (Bookstein 1991). Two of the type II landmarks are situated at the base of the point, defined by the junction of the base and edges of the point. The third type II landmark is located at the tip, defined by the junction of the two blade edges. In order to better define the blades, digital "combs" were used to place pseudolandmarks (type III landmarks) along the edges of each blade. Prior to digitizing, two digital combs were superimposed on each image using H.D. Sheet's MakeFan6 shareware program (www.canisius.edu/~sheets/morphsoft.html). Combs are line segments with equally spaced perpendicular lines that are used for placing landmarks at regular intervals on objects without many obvious landmarks. The first comb was placed between the lower basal landmark and the tip landmark. MakeFan was then used to create eight equally spaced perpendicular lines between the two type II landmarks. The same procedure was followed to create a comb for the upper edge of the blade. The pseudolandmarks were placed at the intersections of the lines of the combs and the edges of the blade. In total, 19 landmarks were digitized for each artifact (Fig. 11.2). Landmarks were digitized using tpsDig2 shareware (Rohlf 2002).

3. *Superimposition of landmarks*. The superimposition of landmarks was accomplished using the generalized orthogonal least-squares Procrustes procedure (Rohlf 2003; Rohlf and Slice 1990). Although the digitized artifacts were all photographed using the same procedure and were orientated similarly, the landmark configurations had to be aligned to avoid minor discrepancies arising from the digitizing process. The generalized Procrustes analysis (GPA) uses three steps to align the landmarks associated with each specimen. First, GPA centers the set of landmark coordinates at their origin, or centroid, and scales all the configurations to unit centroid size. Centroid size is a measure of the overall size of a specimen computed as the square root of the sum of the squared distances

from all the landmarks to the centroid. Second, the GPA procedure determines the mean or consensus configuration. Lastly, GPA rotates each landmark configuration so as to minimize the sum-of-squared residuals for the sample. Steps 2 and 3 are repeated iteratively until convergence is achieved.

4. *Specimens in shape space projected to tangent space*. After the GPA has been performed, landmarks associated with each specimen correspond to locations in Kendall's shape space (Slice 2001). Procrustes distances refer to the distances between all pairs of specimens in the shape space (Bookstein 1991). In order to perform traditional statistical analyses on the shape data they must be projected to a tangent Euclidean space (Rohlf 1998). To obtain the smallest amount of shape variation in tangent space, the mean form or consensus configuration is used as the point of tangency. The consensus configuration for the total sample of points derived from the GPA procedure is shown in Fig. 11.3. Using the consensus configuration as the point of tangency, we tested if the amount of shape variation in the point data is small enough to permit statistical analyses to be

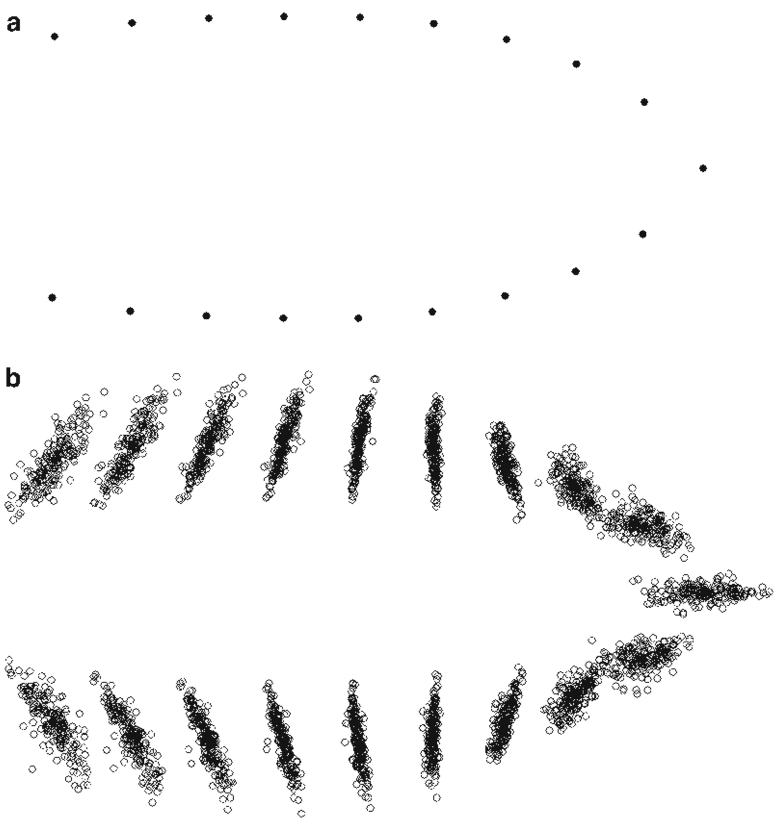

Fig. 11.3 Results of the superimposition method using the generalized orthogonal least-squares Procrustes procedure. (**a**) Consensus configuration of 186 projectile point landmark configurations. (**b**) Variation in projectile point landmark configurations after being translated, scaled, and rotated

performed in the linear tangent space approximate to Kendall's nonlinear shape space. This is accomplished by regressing the distances in the tangent space against the Procrustes distances to determine if the relationship is linear. This test was carried out using the tpsSmall program (Rohlf 2002). The correlation between the two distances was found to be very strong (correlation = 0.9999; root MS error = 0.0001), indicating a good fit between the specimens in shape space and the linear tangent space.

5. *Extraction of partial warps and the uniform component*. Partial warps and the uniform component were computed using the tpsRelw program (Rohlf 2002). A partial warp is an eigenvector of the bending energy matrix that describes local deformation along a coordinate axis. A uniform component expresses global information on deformation. The first uniform component accounts for stretching along the x-axis of a configuration, whereas the second uniform component accounts for variation along the y-axis. Together, the partial warps and the uniform component comprise the weight matrix and represent all information about the shape of specimens. Partial warps and the uniform component can be used in traditional multivariate analyses (Rohlf et al. 1996; Slice 2005).

Having extracted the partial warps and uniform component matrices, we tested the hypothesis that blade shape distinguishes Clovis, Folsom, and Plainview points. We began by subjecting both the partial warps and uniform component matrices to a multivariate analysis of variance (MANOVA). In the first two MANOVAs, we included all specimens and used type as the grouping variable. Since these MANOVAs were significant, we then performed a series of MANOVAs in which the three sets of specimens were compared on a pairwise basis. The goal of these analyses was to determine which types differ significantly. Because MANOVA assumes that group distributions are multivariate-normal with homogeneous covariance matrices, we estimated p-values from a null distribution simulated by random permutation (5,000 iterations). Bonferroni correction was employed in the pairwise analyses. Subsequently, we subjected the partial warps and the uniform component to a discriminant function analysis (DFA) in which point type was used as the grouping variable. The MANOVAs were carried out in MATLAB 6.0 (release 12) using statistical functions written by R.E. Strauss (Strauss 2008). The DFAs were conducted in SPSS 10.0.1.

Subsequently, we carried out two analyses to test the hypothesis that resharpening renders Clovis, Folsom, and Plainview points indistinguishable. In these analyses, we used point area as a proxy for the amount of resharpening on the grounds that smaller points are more likely to have been resharpened than larger points. The point areas were taken from Buchanan (2005, 2006) and Buchanan et al. (2007). We used the point areas rather than the centroid sizes produced by the GPA because they were calculated from more landmarks than used in the present study (36 vs. 19) and included landmarks demarcating the basal portion of points. The base is important to take into account when measuring point size because it ranges from concave to convex in shape both among and within types. In the first analysis, we used the mean point area for each set of points to divide the set in question into a

group of large points and a group of small points. We then subjected the shape data to a DFA in which type/size was used as the grouping variable. Next, we tested for differences in the proportions of misclassified points between the large and small groups. The second analysis was identical to the first analysis except three size groups were utilized (small, medium, and large). These analyses were conducted in SPSS 10.0.1.

Results

Table 11.2 summarizes the results of the MANOVA carried out to test the hypothesis that blade shape distinguishes Paleoindian projectile point types. As noted earlier, the MANOVAs in which specimens assigned to all three types were included were significant. This indicates that at least two of the three types have distinctive blade shapes. The MANOVA in which Clovis and Folsom specimens were compared was significant. The MANOVA in which Clovis and Plainview were compared was also significant, albeit less so than the Clovis vs. Folsom one. In contrast, the MANOVA in which Folsom and Plainview were compared was not significant. Thus, the MANOVA analyses partially support the hypothesis that blade shape distinguishes Paleoindian projectile point types. They suggest that blade shape distinguishes Clovis points from Folsom points, and to a lesser extent Clovis points from Plainview points, but does not distinguish Folsom points from Plainview points.

The results of the DFA in which types were used as the grouping variable are shown in Table 11.3. There was no misclassification between Clovis and Folsom points. Twenty-nine percent of Clovis points were misclassified as Plainview points, and 5% of Plainview points were misclassified as Clovis points.

Table 11.2 Results from multivariate analysis of variance tests of shape variables by projectile point type

Types compared	*F*	*p*-value
Clovis, Folsom, Plainview	2.33	0.0002*
Clovis, Folsom	4.13	0.0002*
Clovis, Plainview	2.46	0.0002*
Folsom, Plainview	1.70	0.0218

*Significant at the 0.0125 alpha level in accordance with the Bonferroni correction

Table 11.3 Classification results from a discriminant function analysis of shape variables by projectile point type

	Predicted group membership			
Type	Clovis	Folsom	Plainview	Total
Clovis	20 (71.4)	0	8 (28.6)	28
Folsom	0	27 (57.4)	20 (42.6)	47
Plainview	5 (4.5)	12 (10.8)	94 (84.7)	111

Percentages are shown in parentheses after the number of points in a predicted group

Forty-three percent of Folsom points were misclassified as Plainview points, and 11% of Plainview points were misclassified as Folsom points. Thus, the lowest level of misclassification occurred with Clovis and Folsom, an intermediate level with Clovis and Plainview, and the highest with Folsom and Plainview. As such, the results of the DFA in which types were used as the grouping variable were consistent with the results of the MANOVAs. They also suggest that blade shape distinguishes Clovis points from Folsom points, and to a lesser extent Clovis points from Plainview points, but does not distinguish Folsom points from Plainview points.

The results of the DFA in which each set of points was divided into a small group and a large group are presented in Table 11.4. As in the analyses carried out to test the assumption that blade shape distinguishes Paleoindian point types, there was no misclassification between Clovis and Folsom points, but there was misclassification between Clovis and Plainview points, and between Folsom and Plainview points. Fourteen percent of the large Clovis points were classified as large Plainview points. Twenty-one percent of the small Clovis points were misclassified as small Plainview points, and another 7% were misclassified as large Plainview points. Eight percent of the large Folsom points were misclassified as small Plainview points, and 25% of the large Folsom points were misclassified as large Plainview points. Seventeen percent of the small Folsom points were misclassified as small Plainview points, and the same percentage of the small Folsom points were misclassified as large Plainview points. Two percent of the large Plainview points were misclassified as large Clovis points, and 5% were misclassified as large Folsom points. Six percent of the small Plainview points were misclassified as small Clovis points, 7% were misclassified as large Folsom points, and 11% were misclassified as small Folsom points. None of the differences in misclassification rate between small and large points was significant (Table 11.5). Thus, the DFA in which each set of points was divided into a small group and a large group does not support the hypothesis that resharpening renders Clovis, Folsom, and Plainview points indistinguishable.

The results of the DFA in which each set of points was divided into large, medium, and small groups are shown in Table 11.6. There was no misclassification between Clovis and Folsom points in any of the three size grades. Eleven percent of small Clovis was misclassified as small Plainview. Ten percent of medium Clovis was misclassified as medium Plainview, and the same percentage of medium Clovis was misclassified as large Plainview. Eleven percent of large Clovis was misclassified as medium Plainview. Seven percent of small Folsom was misclassified as small Plainview, 20% of small Folsom was misclassified as medium Plainview, and 7% of small Folsom was misclassified as large Plainview. Thirteen percent of medium Folsom was misclassified as small Plainview, 6% of medium Folsom was misclassified as medium Plainview, and 6% of medium Folsom was misclassified as large Plainview. Six percent of large Folsom was misclassified as small Plainview, 6% of large Folsom was misclassified as medium Plainview, and 25% of large Folsom was misclassified as large Plainview. Eleven percent of small Plainview was misclassified as small Folsom, and the same percentage of small Plainview was misclassified as

Table 11.4 Classification results from a discriminant function analysis of shape variables by two size grades (large and small) within types

	Predicted group membership						
Type	Clovis-small	Clovis-large	Folsom-small	Folsom-large	Plainview-small	Plainview-large	Total
Clovis-small	7 (50)	3 (21.4)	0	0	3 (21.4)	1 (7.1)	14
Clovis-large	1 (7.1)	11 (78.6)	0	0	0	2 (14.3)	14
Folsom-small	0	0	14 (60.9)	1 (4.3)	4 (17.4)	4 (17.4)	23
Folsom-large	0	0	1 (4.2)	15 (62.5)	2 (8.3)	6 (25)	24
Plainview-small	3 (5.5)	0	6 (10.9)	4 (7.3)	33 (60)	9 (16.4)	55
Plainview-large	0	1 (1.8)	0	3 (5.4)	9 (16.1)	43 (76.8)	56

Percentages are shown in parentheses after the number of points in a predicted group

Table 11.5 Misclassification rates from a discriminant function analysis of shape variables by two size grades (large and small) within types

Type	Number misclassified	Percent misclassified	p-Value	Bootstrapped p-value
Clovis-small	7/14	50	0.0984	0.2432
Clovis-large	3/14	21		
Folsom-small	9/23	39	0.9085	1.0000
Folsom-large	9/24	38		
Plainview-small	22/55	40	0.0533	0.0680
Plainview-large	13/56	23		

Results of significance tests for the difference in proportions misclassified between small and large points are given in the last two columns. Bootstrapped p-values are derived from 5,000 iterations

large Folsom. Three percent of medium Plainview was misclassified as small Clovis, and the same percentage of medium Plainview was misclassified as medium Folsom. Three percent of large Plainview was misclassified as large Clovis, and the same percentage of large Plainview was misclassified as large Folsom. The misclassification rate by type/size is shown in Table 11.7. The results of comparisons in the misclassification rates among the three size grades within types are shown in Table 11.8. None of the proportions of misclassified points was significantly different among large, medium, and small groups of points within types. Thus, the DFA in which each set of points was divided into large, medium, and small groups does not support the hypothesis that resharpening renders Clovis, Folsom, and Plainview points indistinguishable.

Discussion

We conducted the study reported here to evaluate two hypotheses. The first was that blade shape distinguishes Clovis, Folsom, and Plainview points. To evaluate this hypothesis we conducted MANOVA and DFA analyses on shape variables. The MANOVA results showed that blade shape is significantly different among the types. However, pairwise MANOVAs found that blade shape distinguishes Clovis points from Folsom points, and to a lesser extent Clovis points from Plainview points, but does not distinguish Folsom points from Plainview points. The DFA was consistent with the MANOVAs. The shape variables correctly discriminated Clovis from Folsom points. Clovis and Plainview points were discriminated less clearly, and Folsom and Plainview points were discriminated at the worst rate. Therefore, our results support the hypothesis that blade shape can be used as a character to distinguish between Clovis and Folsom points. Our results are less clear about the ability of blade shape to distinguish between Clovis and Plainview points. Lastly, the low level of discrimination between Folsom and Plainview points suggests that blade shape cannot be used to discriminate the two types.

Table 11.6 Classification results from a discriminant function analysis of shape variables by three size grades (large, medium, and small) within types

	Predicted group membership									
Type	Clovis-small	Clovis-medium	Clovis-large	Folsom-small	Folsom-medium	Folsom-large	Plainview-small	Plainview-medium	Plainview-large	Total
Clovis-small	7 (77.8)	0	1 (11.1)	0	0	0	1 (11.1)	0	0	9
Clovis-medium	0	7 (70)	1 (10)	0	0	0	0	1 (10)	1 (10)	10
Clovis-large	1 (11.1)	0	7 (77.8)	0	0	0	0	1 (11.1)	0	9
Folsom-small	0	0	0	9 (60)	0	1 (6.7)	1 (6.7)	3 (20)	1 (6.7)	15
Folsom-medium	0	0	0	2 (12.5)	10 (62.5)	0	2 (12.5)	1 (6.3)	1 (6.3)	16
Folsom-large	0	0	0	0	1 (6.3)	9 (56.3)	1 (6.3)	1 (6.3)	4 (25)	16
Plainview-small	0	0	0	4 (10.8)	4 (10.8)	0	21 (56.8)	7 (18.9)	1 (2.7)	37
Plainview-medium	1 (2.7)	0	0	0	1 (2.7)	0	4 (10.8)	26 (70.3)	5 (13.5)	37
Plainview-large	0	0	1 (2.7)	0	0	1 (2.7)	3 (8.1)	3 (8.1)	29 (78.4)	37

Percentages are shown in parentheses after the number of points in a predicted group

Table 11.7 Misclassification rates from a discriminant function analysis of shape variables by three size grades (large, medium, and small) within types

Type	Number misclassified	Percent misclassified
Clovis-small	2/9	22
Clovis-medium	3/10	30
Clovis-large	2/9	22
Folsom-small	6/15	40
Folsom-medium	6/16	38
Folsom-large	7/16	44
Plainview-small	16/37	43
Plainview-medium	11/37	30
Plainview-large	8/37	22

Table 11.8 Results of significance tests for the difference in proportions misclassified between small and medium and small and large points within types

Comparison	*p*-Value	Bootstrapped *p*-value
Clovis-small to Clovis-medium	0.6981	1.0000
Clovis-small to Clovis-large	1.0000	1.0000
Folsom-small to Folsom-medium	0.8864	1.0000
Folsom-small to Folsom-large	0.8323	1.0000
Plainview-small to Plainview-medium	0.2227	0.3378
Plainview-small to Plainview-large	0.0412	0.0784

Bootstrapped *p*-values are derived from 5,000 iterations

The second hypothesis we tested is that resharpening renders Clovis, Folsom, and Plainview points indistinguishable. To evaluate this hypothesis we carried out two size grade analyses. We reasoned that, if the hypothesis is correct, the misclassification rate for small points should be statistically significantly higher than the misclassification rate for larger points, since the former are more likely to have been subject to resharpening than the latter. Tests for differences in the proportion of misclassifications between points of different type/size revealed that none of the proportions were different. Therefore, this part of our study suggests that resharpening does not alter the distinctive blade shapes of points associated with each type. The available evidence suggests that resharpening occurs primarily on the blades of Paleoindian points, probably as a result of rejuvenation work on still-hafted points (Bement 2002; Collins 1999; Cox 1986; Gardner 1983; Gardner and Verrey 1979). Thus, our study indicates that the resharpening hypothesis does not hold for Paleoindian projectile points from the Southern High Plains.

Our finding that resharpening does not result in the convergence of blade shapes among Paleoindian projectile point types is in line with the results of an assessment of the impact of resharpening on point types in the Great Basin conducted by Bettinger et al. (1991) in response to claims made by Flenniken and Wilke (1989). Flenniken and Wilke (1989) analyzed eight assemblages of dart points from the Great Basin and argued that 21 of the 23 types represented in the assemblages are in fact reduction sequence stages rather than types. Bettinger et al. (1991) tested

Flenniken and Wilke's hypothesis by weighing points representing the putative ancestral and derivative types. Their analysis showed that the types that were supposedly created by resharpening were consistently heavier than the ancestral forms, which is inconsistent with Flenniken and Wilke's hypothesis. Together, the results of our study and those obtained by Bettinger et al. (1991) indicate that, contrary to what Flenniken and Raymond contend, resharpening does not automatically led to convergence of projectile point types. Rather, it appears that in some cases that resharpening is carried out in such a way as to maintain a given blade shape.

One implication of our study is that the significant overlap in Folsom and Plainview blade shape is independent of resharpening. One possible explanation for the overlap is that some of the points and/or assemblages have been misclassified. We consider this unlikely given that the assemblages in our sample were identified as belonging to a particular type based on a combination of attributes including diagnostic features on the points themselves, radiocarbon ages, and stratigraphic evidence. There are two other possible explanations for the overlap. One is that Folsom and Plainview descended from a common ancestor and that blade shape is a plesiomorphic character. The other is that Folsom and Plainview points share similar blade shape due to convergent cultural evolution. Folsom and Plainview points were both used for hunting bison and the blade shape of both types may have been honed to an optimal functional efficiency for this task. It should be possible to determine which of these hypotheses is most likely to be correct with cladistic analysis (Buchanan and Collard 2007; Lycett 2007, 2009; O'Brien et al. 2001) and experiments designed to determine performance characteristics (O'Brien et al. 1994).

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References

Amick, D.S., Hofman, J.L., and Rose, R.O., 1989. The Shifting Sands Folsom-Midland site in Texas. *Current Research in the Pleistocene* 6: 1–3.

Anderson, D.G. and Faught, M.K., 2000. Palaeoindian artefact distributions: evidence and implications. *Antiquity* 74: 507–513.

Bamforth, D.B., 1991. Flintknapping skill, communal hunting, and Paleoindian projectile point typology. *Plains Anthropologist* 36: 309–322.

Bement, L.C., 1999a. *Bison Hunting at Cooper Site. Where Lightning Bolts Drew Thundering Herds*. University of Oklahoma Press, Norman, OK.

Bement, L.C., 1999b. View from a kill: the Cooper Site Folsom lithic assemblage. In *Folsom Lithic Technology. Explorations in Structure and Variation*, edited by D.S. Amick, pp. 111–121. International Monographs in Prehistory, Archaeological Series 12, Ann Arbor, MI.

Bement, L.C., 2002. Pickin' up the pieces: Folsom projectile point re-sharpening technology. In *Folsom Technology and Lifeways*, edited by J.E. Clark, M.B. Collins, pp. 135–140. Special Publications No. 4, Lithic Technology, University of Tulsa, Tulsa, OK.

Bettinger, R.L., O'Connell, J.F., and Thomas, D.H., 1991. Projectile points as time markers in the Great Basin. *American Anthropologist* 93: 166–172.

Boldurian, A.T., 1990. Lithic technology at the Mitchell Locality of Blackwater Draw: a stratified Folsom Site in eastern New Mexico. *Plains Anthropologist Memoir* 24, 1–103.

Boldurian, A.T., and Cotter, J.L., 1999. *Clovis Revisited. New Perspectives on Paleoindian Adaptations from Blackwater Draw, New Mexico*. The University Museum, University of Pennsylvania, Philadelphia.

Bookstein, F.L., 1991. *Morphometric Tools for Landmark Data: Geometry and Biology*. Cambridge University Press, Cambridge.

Bradley, B.A., and Stanford, D.J., 1987. The Claypool study. In *The Horner Site: The Type Site of the Cody Cultural Complex*, edited by G.C. Frison and L.C. Todd, pp. 405–434. Academic Press, New York.

Buchanan, B., 2002. Folsom lithic procurement, tool use, and replacement at the Lake Theo Site, Texas. *Plains Anthropologist* 47: 121–146.

Buchanan, B., 2005. Cultural transmission and stone tools: a study of early Paleoindian technology in North America. Unpublished PhD dissertation, Department of Anthropology, University of New Mexico, Albuquerque, USA.

Buchanan, B., 2006. An analysis of Folsom projectile point resharpening using quantitative comparisons of form and allometry. *Journal of Archaeological Science* 33: 185–199.

Buchanan, B. and Collard, M.C. 2007, Investigating the peopling of North America through cladistic analyses of early Paleoindian projectile points. *Journal of Anthropological Archaeology* 26: 366–393.

Buchanan, B., Johnson, E., Strauss, R.E., and Lewis, P.J., 2007. A morphometric approach to assessing Late Paleoindian projectile point variability on the Southern High Plains. *Plains Anthropologist* 52: 279–299.

Buchanan, B., Litwinionek, L., Johnson, E., Holliday, V.T., and Hicks, J.K., 1996. Renewed investigations at Milnesand and Ted Williamson Paleoindian sites, Southern High Plains. *Current Research in the Pleistocene* 13: 8–10.

Cannon, M.D., 2004. Geographic variability in North American mammal community richness during the Terminal Pleistocene. *Quaternary Science Reviews* 23: 1099–1123.

Collins, M.B., 1999. Clovis and Folsom lithic technology on and near the Southern Plains: similar ends, different means. In *Folsom Lithic Technology: Explorations in Structure and Variation*, edited by D.S. Amick, pp. 12–38. International Monographs in Prehistory, Archaeological Series 12. Ann Arbor, MI.

Cotter, J.L., 1937. The occurrence of flints and extinct animals in Pluvial deposits near Clovis, New Mexico. Part IV.-Report on Excavation at the Gravel Pit, 1936. *Proceedings of the Academy of Natural Sciences of Philadelphia* 89: 1–16.

Cotter, J.L., 1938. The occurrence of flints and extinct animals in Pluvial deposits near Clovis, New Mexico. Part VI.-Report on Field Season of 1937. *Proceedings of the Academy of Natural Sciences of Philadelphia* 90: 113–117.

Cox, S.L., 1986. A re-analysis of the Shoop site. *Archaeology of Eastern North America* 14: 101–170.

Crabtree, D., 1966. A stoneworker's approach to analyzing and replicating the Lindenmeier Folsom. *Tebiwa* 9: 3–39.

Ellis, C., 2004. Understanding “Clovis” fluted point variability in the northeast: a perspective from the Debert Site. *Canadian Journal of Archaeology* 28: 205–253.

Flenniken, J.J. and Raymond, A.W., 1986. Morphological projectile point typology: replication experimentation and technological Analysis. *American Antiquity* 51: 603–614.

Flenniken, J.J. and Wilke, P.J., 1989. Typology, technology, and chronology of Great Basin dart points. *American Anthropologist* 91: 149–158.

Gardner, W.M., 1983. Stop me if you’ve heard this one before: the Flint Run Paleoindian complex revisited. *Archaeology of Eastern North America* 11: 49–64.

Gardner, W.M. and Verrey, R.A., 1979. Typology and chronology of fluted points from the Flint Run area. *Pennsylvania Archaeologist* 49: 13–46.

Harrison, B.R. and Killen, K.L., 1978. *Lake Theo: A Stratified, Early Man Bison Butchering and Camp Site, Briscoe County, Texas*. Special Archeological Report, 1, Panhandle-Plains Historical Museum, Canyon, TX.

Harrison, B.R. and Smith, H.C., 1975. A test excavation of the Lake Theo site Briscoe County, Texas. *Panhandle-Plains Historical Review* 48: 70–106.

Hartwell, W.T., 1995. The Ryan’s site cache: comparisons to Plainview. *Plains Anthropologist* 40(152): 165–184.

Haynes, C.V., Jr., 1980. The Clovis culture. *Canadian Journal of Anthropology* 1: 115–121.

Haynes, G., 2002. *The Early Settlement of North America*. Cambridge University Press, Cambridge.

Hester, J.J., 1972. Blackwater Draw Locality No. 1: a stratified early Man Site in Eastern New Mexico. Fort Burgwin Research Center Publication No. 8, Ranchos de Taos, NM

Hofman, J.L, 1991. Folsom land use: projectile point variability as a key to mobility. In *Raw Material Economies Among Prehistoric Hunter-Gatherers*, edited by A. Montet-White and S. Holen, pp. 335–355. University of Kansas, Publications in Anthropology 19. University of Kansas Press, Lawrence.

Hofman, J.L, 1992. Recognition and interpretation of Folsom technological variability on the Southern Plains. In *Ice Age Hunters of the Rockies*, edited by D.J. Stanford and J.S. Day, pp. 193–224. University Press of Colorado, Niwot.

Hofman, J.L., Amick, D.S., and Rose, R.O., 1990. Shifting Sands: a Folsom-Midland assemblage from a campsite in western Texas. *Plains Anthropologist* 35: 221–253.

Holliday, V.T., 1995. Stratigraphy and Paleoenvironments of Late Quaternary Valley Fills on the Southern High Plains. *Geological Society of America Memoir* 186: 1–136.

Holliday, V.T., 1997. *Paleoindian Geoarchaeology of the Southern High Plains*. University of Texas Press, Austin.

Holliday, V.T., 2000. The evolution of Paleoindian geochronology and typology on the Great Plains. *Geoarchaeology* 15: 227–290.

Holliday, V.T., Johnson, E., and Stafford, T.W., Jr., 1999. AMS radiocarbon dating of the type Plainview and Firstview (Paleoindian) type assemblages. *American Antiquity* 64: 444–454.

Holliday, V.T., Haynes, C.V., Jr., Hofman, J.L., and Meltzer, D.J., 1994. Geoarchaeology and geochronology of the Miami (Clovis) site, Southern High Plains of Texas. *Quaternary Research* 41: 234–244.

Howard, C.D., 1990, The Clovis point: characteristics and type description. *Plains Anthropologist* 35: 255–262.

Howard, E.B., 1935, Occurrence of flints and extinct animals in Pluvial deposits near Clovis, New Mexico, Part I,-Introduction. *Proceedings of the Academy of Natural Sciences of Philadelphia* 87: 299–303.

Hunt, C.B., 1967. *Physiography of the United States*. W.H. Freeman, San Francisco.

Johnson, E. (editor), 1987. *Lubbock Lake. Late Quaternary Studies on the Southern High Plains*. Texas A&M University Press, College Station.

Johnson, E., Holliday, V.T., Warnica, J., and Williamson, T., 1986. The Milnesand and Ted Williamson Paleoindian sites, east-central New Mexico. *Current Research in the Pleistocene* 3: 9–11.

Knudson, R., 1983, *Organizational Variability in Late Paleo-Indian Assemblages*. Washington State University, Laboratory of Anthropology, Reports on Investigations 60, Pullman.

Leonhardy, F.C. (editor), 1966. *Domebo: A Paleo-Indian Mammoth Kill in the Prairie-Plains*. Contributions of the Museum of the Great Plains No. 1, Lawton, OK.
Lycett, S.J., 2007. Why is there a lack of Mode 3 Levallois technologies in East Asia? A phylogenetic test of the Movius-Schick hypothesis. *Journal of Anthropological Archaeology* 26: 541–575.
Lycett, S.J., 2009. Are Victoria West cores 'Proto-Levallois'? A phylogenetic assessment. *Journal of Human Evolution* 56: 175–191.
Meltzer, D.J., 2006. *Folsom: New Archaeological Investigations of a Classic Paleoindian Bison Kill*. University of California Press, Berkeley.
Morrow, J.E., and Morrow, T.A., 1999. Geographic variation in fluted projectile points: a hemispheric perspective. *American Antiquity* 64: 215–231.
O'Brien, M.J., Darwent, J., and Lyman, R.L., 2001. Cladistics is useful for reconstructing archaeological phylogenies: Palaeoindian points from the southeastern United States. *Journal of Archaeological Science* 28: 1115–1136.
O'Brien, M.J., Holland, T.D., Hoard, R.J., and Fox, G.L., 1994. Evolutionary implications of design and performance characteristics of prehistoric pottery. *Journal of Archaeological Method and Theory* 1: 259–304.
Rohlf, F.J., 1998. On applications of geometric morphometrics to studies of ontogeny and phylogeny. *Systematic Biology* 47: 147–158.
Rohlf, F.J., 2002. TPS shareware series. Department of Ecology and Evolution, State University of New York, Stony Brook, NY. http://life.bio.sunysb.edu/morph.
Rohlf, F.J., 2003. Bias and error in estimates of mean shape in geometric morphometrics. *Journal of Human Evolution* 44: 665–683.
Rohlf, F.J., and Marcus, L.F., 1993. A revolution in morphometrics. *Trends in Ecology and Evolution* 8: 129–132.
Rohlf, F.J., and Slice, D.E., 1990. Extensions of the Procrustes method for the optimal superimposition of landmarks. *Systematic Zoology* 39: 40–59.
Rohlf, F.J., Loy, A., and Corti, M., 1996. Morphometric analysis of Old World Talpidae (Mammalia, Insectivora) using partial-warp scores. *Systematic Biology* 45: 344–362.
Sellards, E.H., 1938. Artifacts associated with fossil elephant. *Bulletin of the Geological Society of America* 49: 999–1010.
Sellards, E.H., 1952. *Early Man in North America*. The University of Texas Press, Austin.
Sellards, E.H., 1955. Fossil bison and associated artifacts from Milnesand, New Mexico. *American Antiquity* 20: 336–344.
Sellards, E.H., Evans, G.L., and Meade, G.E., 1947. Fossil bison and associated artifacts from Plainview, Texas. *Bulletin of the Geological Society of America* 58: 927–954.
Shott, M.J. and Ballenger, J., 2007. Biface reduction and the measurement of Dalton curation: a southeastern case study. *American Antiquity* 72: 153–175.
Slice, D.E., 2001. Landmark coordinates aligned by Procrustes analysis do not lie in Kendall's shape space. *Systematic Biology* 50: 141–149.
Slice, D.E. (editor), 2005. *Modern Morphometrics in Physical Anthropology*. Kluwer Academic, New York.
Speer, R.D., 1983. History of the Plainview site. In *Guidebook to the Central Llano Estacado*, edited by V.T. Holliday, pp. 127–131. Friends of the Pleistocene South-Central Cell 1983 Field Trip, International Center for Arid and Semi-Arid Land Studies, Texas Tech University and Museum of Texas Tech University, Lubbock.
Strauss, R.E., 2008. Matlab Statistical Functions [computer software]. Retrieved March, 2008, from http://www.faculty.biol.ttu.edu/Strauss/Matlab/matlab.htm.
Taylor, R.E., Haynes, C.V., Jr., and Stuiver, M., 1996. Clovis and Folsom age estimates: stratigraphic context and radiocarbon calibration. *Antiquity* 70: 515–525.
Velhagen, W.A., and Roth, V.L., 1997. Scaling the mandible in squirrels. *Journal of Morphology* 232: 107–132.
Warnica, J.M., 1966. New discoveries at the Clovis Site. *American Antiquity* 31: 345–357.
Warnica, J.M., and Williamson, T., 1968. The Milnesand site – revisited. *American Antiquity* 33: 16–24.

Wheat, J.B., 1976. Artifact life histories: cultural templates, typology, evidence and inference. In *Primitive Art and Technology*, edited by J. Raymond, B. Loveseth, C. Arnold, and G. Reardon, pp. 7–15. The University of Calgary Archaeological Association, Calgary.

Wheat, J.B., 1977. Technology, typology, and use patterns at the Jurgens site. In *Paleoindian Lifeways*, edited by E. Johnson, pp.48–64. The Museum Journal, West Texas Museum Association, Lubbock.

Zelditch, M.L, Swiderski, D.L., Sheets, H.D., and Fink, W.L., 2004. Geometric morphometrics for biologists: a primer. Elsevier Academic Press, Amsterdam.

Chapter 12
Stone-Tool Demography: Reduction Distributions in North American Paleoindian Tools

Michael J. Shott

Abstract Stone tools "age" by reduction during use. Like individuals, each tool "ages" (is reduced) to some particular degree; like populations, sets of tools "age" (are reduced) to varying degrees expressed as reduction distributions. I fit distributions of North American Paleoindian tools to mathematical models, both for efficient description and to identify processes that govern discard. Reduction analysis is the thoughtful use of surprisingly simple measurements and practices to reveal both dimensions of past behavior and how the archaeological record formed.

Classification and process being equally integral to the scientific enterprise, an enduring tension exists between essentialist and materialist habits of scientific thought. In essentialism, analytical subjects reflect "a limited number of constant and sharply delimited *eide* or essences" (Mayr 1991:40), within which variation is trivial. In premodern biology, for instance, species were natural kinds, their individuals merely imperfect realizations of the ideal essence that was the kind. In contrast, materialism dismisses kinds for the clutter that is complex variation among individuals, be they rocks, zebras, or people. In its view, kinds are merely abstractions or constructions from a continuously varying reality.

Essentialism may prevail in the physical sciences. One molecule of water must be identical in structure and behavior to any other, or chemists cannot speak of water as an essential kind or category of matter. In social and evolutionary sciences, however, it is absurd to suppose that individuals – be they stone tools or people – embody Platonic essences such that they are functionally equivalent. For nearly two centuries, these sciences have been materialistic in perspective.

Yet essentialist habits of thought endure even in the social and natural scientists. In stone-tool studies, for instance, essentialism persists in how we treat patterns of

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variation in our subjects, the meaning that we invest in defined types, and in the limits we arbitrarily impose upon their analysis.

The Reduction Thesis

It is truism to state that all stone tools except for cores and cobbles are themselves flakes struck from larger pieces during a reduction process, and that retouched tools themselves are, first, produced and, second, often resharpened or repaired during use in a process to which reduction is intrinsic. Like eggs and omelettes, if you wish to make, use and refurbish stone tools, then you must break some rocks. Reduction is both obvious and intrinsic to the process of making, using, and maintaining stone tools.

Historically, lithic analysis took an essentialist view of types, which burdened it with two corollary and unexamined assumptions. First, tool types as Platonic essences possess integrity as joint morphological and functional kinds. There is no continuity, metric or formal, between Middle Paleolithic single, double and convergent scrapers, Australian steep-edge scrapers and flat scrapers, or North American Pickwick and Elora points. Second, the size and form in which archaeologists find tools are the size and form in which they were used (excepting fracture and other distortions).

No matter how much or how often the plain facts of lithic reduction were acknowledged, it is only by degree that lithic studies have assimilated them into analysis. Thus, a clear trend in the past two decades of lithic analysis is the growing concern for reduction. Earlier harbingers of the trend are both archaeological and ethnographic (e.g., Frison 1968; Hayden 1977; Tindale 1965). By the 1980s, archaeologists possessed a working understanding of the reduction process and predisposed to exploring its implications in a range of lithic contexts. If not necessarily the first, certainly the best known of these efforts was by Dibble (e.g., 1987) and colleagues. Standing in a clear line of descent from Hayden's pioneering work, these archaeologists concluded that many types of retouched flakes and notches defined by European Paleolithic archaeologists largely (not entirely) marked arbitrary junctures in several continua of flake-tool reduction. Their argument, even now only partly assimilated in a Paleolithic archaeology still in thrall to typological thinking, is that types are not fossil templates or cultural markers, merely patterns and degrees of reduction of flake tools.

At the same time, Hoffman (1985) brought a reduction perspective to the study of North American bifaces ("points"). Hoffman showed that a group of biface types defined in the American Southeast (e.g., Pickwick, Elora, Cotaco Creek) actually were a family of related types or, more accurately, arbitrary subdivisions size and form in several trajectories of the resharpening and reduction of original large stemmed bifaces.

This is the reduction thesis (Shott 2005, 2007), with far-reaching implications for essentialist concepts. Lithic reduction, for instance, compromises the integrity of tool types. Reduction effects are recognized in many tool types of many ages from many parts of the world. Besides studies noted above, reduction and its effects on tool size and form – and therefore on typology – register clearly in Paleolithic tools (Barton et al. 1996; De Bie 2007:37–38; Holdaway et al. 1996; Neeley and Barton 1994), North American stemmed bifaces (Truncer 1990; Wheat 1974) and

unifaces (Grimes and Grimes 1985; Morrow 1996; Shott 1995), and Australian flake tools (Hiscock and Attenbrow 2003).

Notionally, reduction occurs flake by flake. But it is better understood as a continuous process, both because the incremental units – retouch flakes – ordinarily are very small relative to the tool and because reduction is measured by continuous variables or dimensions like length and width. If reduction is continuous then tools vary in continuous terms, so cannot approximate Platonic essences. Any types formed in complex reduction trajectories are empirical tendencies, not essential types. Zebras never become giraffes, but Oldowan cobbles become discoids become scrapers (Sahnouni et al. 1997; Shott 2008) and Pickwick points become Eloras (Hoffman 1985:580). Defining types in these trajectories is like trying to slice a piece of water from a flowing stream.

This is not to deny the sometime-validity of typological concepts. It is, however, to deny the necessity of essential types and to acknowledge that much variation in stone-tool size and form owes to continuous reduction combined with modes of use and retouch. More important still, if reduction is a continuous process, then it is best measured in ways commensurate with that process, and its theoretical corollaries demand equivalent treatment.

Measuring Reduction

Reduction analysis in lithic studies was initially concerned to demonstrate the fact of reduction. Studies cited above accomplished this goal in great abundance. Once the fact of reduction is accepted, attention passes naturally to the measurement of its degree and pattern. Despite the challenges of measurement, this branch of reduction analysis has witnessed great progress in recent years. Elsewhere (Shott 2005, 2007) I summarized this progress at some length.

Here it suffices to note that, ironically, reduction measurement first was accomplished by means of the typology that it challenged. That is, reduction effects were demonstrated by linking defined types as successive stages of reduction trajectories (e.g., Dibble 1987; Hoffman 1985). Basically, reduction approximated this way is a nominal variable. But only reduction indices grounded in estimates of tools' original size can measure reduction as a ratio-scale, continuous variable. Measuring reduction this way requires comparing the end result – the tool as discarded to enter the archaeological record and thus found by archaeologists – to estimates of its original size and form. Principal approaches involve geometry and allometry.

Geometric Measures

Kuhn's (1990) "Geometric Index of Unifacial Reduction" (GIUR) is the most popular geometric reduction measure (e.g., Hiscock and Attenbrow 2003). Like all methods, the GIUR has limitations, some of which are inherent and others depending on mode or pattern of tool use (Shott 2005:115–118). Australians are its most enthusiastic advocates, yet must acknowledge the geometric necessity of GIUR's constraint where

tools' cross-sections are substantially "flat" because of parallel faces. Eren and Prendergast (2008:67–75) document at length its statistical and theoretical limitations. Advocacy of particular methods is salutary to the limits of their validity and reach, but we must avoid tiresome arguments about the general superiority of particular measures in order to appreciate that the manifest diversity of reduction trajectories and effects requires comparable diversity in reduction measures.

Retouch indices are geometric reduction measures that record type and pattern of invasive retouch across zones that subdivide a flake tool's perimeter (e.g., Andrefsky 2006). This approach too has limitations (Shott 2005:118–119), among which are its reliance upon an arbitrarily selected number of zones and the measurement of degree of invasiveness. Like GIUR, retouch invasiveness indices are useful reduction measures in many cases.

Allometric Measures

Allometry is change in form or proportion as a function of change in size. Flake allometry is based on experimental studies (e.g., Pelcin 1996) that document mechanical constraints on the surface area or mass of flakes exercised indirectly by force and angle of blow and directly by platform size. Those constraints produce statistical patterns that are strong but include too much stochastic noise for precise estimation of flakes' original area or mass (e.g., Shott et al. 1999). Platform allometry has limited value in reduction analysis.

Nevertheless, as they are retouched and reduced tools change more in some dimensions than in others. This too is allometry, documented in Paleolithic (Blades 2003) and ethnoarchaeological (Shott and Weedman 2007) unifaces and in North American (Hoffman 1985; Shott and Ballenger 2007; Shott et al. 2007) and South American (Cardillo 2005; Castiñeira et al. 2007; Iriarte 1995; Suárez 2004:33–34) bifaces. This allometry is documented by remarkably simple measures, typically ratios of a dimension much affected by reduction (e.g., length, blade width, surface area) to dimensions not so affected (typically thickness or haft area).

There are other variants of both geometric and allometric reduction measures, as well as combinations of the approaches. For instance, the elaborate "estimated reduction percentage" (ERP) geometric reduction index (Eren et al. 2005; Eren and Prendergast 2008) involves numerous measurements that simultaneously approximate tool volume and form. More generally, Andrefsky's (2008) recent compendium documents the breadth of current approaches to reduction measurement.

All reduction measures have their limits; no biface-reduction measure, for instance, can be based on the cross-section geometry of flakes or on platform allometry because bifaces lack these features. Even some flake tools are modified extensively before use by trimming or removing features like their platforms. But several indices can be measured on the same specimens, so there are opportunities to compare them (e.g., Eren et al. 2005).

Reduction's Theoretical Freight

The reduction thesis is no mere complication to lithic analysis, but a body of method that considerably expands the scope of inference from stone tools. Besides typological rigor, reduction measures bear upon models of assemblage formation that implicate evolutionary–ecology behavioral models. GIUR correlated with measures of mobility and occupation duration in Folsom assemblages of North America (Surovell 2003:285–287, Tables 6.5–6.7). Elsewhere, Beck's (1995:234–237) selectionist study used reduction measurement to reveal that longevity and the related quality of impact resistance distinguish corner-notched from side-notched North American Great Basin dart points.

These are merely examples of the theoretical significance of reduction analysis. Yet despite its impressive methodological progress, the reduction thesis remains underdeveloped in two key respects. First, reduction analysis has not sufficiently explored its own deeper theoretical, not merely typological, implications. Second, it has yet to appreciate the importance or exploit the theoretical potential of reduction distributions. My purpose is to consider one theoretical implication of the reduction thesis and then to illustrate the value of analyzing reduction distributions in sets of stone tools. In the process, I hope to unify these two underdeveloped branches of reduction analysis into a single approach that at once measures reduction and exploits its theoretical potential.

Reduction and Curation

Reduction has especially profound implications for tool curation, a concept familiar to most lithic analysts. From its inception, curation was freighted with many meanings, most of them qualitative and incapable of measurement. Two common definitions of curation, for instance, are the production of tools in anticipation of future use and the practice of carrying tools between places (Binford 1973).

Originally, curation had great heuristic value. But its various, not always consistent, meanings permitted archaeologists to give the same name to different observations about or conclusions from their data. What is more, curation was not used analytically so much as it was invoked to explain particular characteristics of assemblages (e.g., their reliance upon particular toolstones, their proportions of retouched tools). At length, curation became an essential condition opposed to a mutually exclusive thing called "expediency," and it was thought to describe assemblages, not their constituent tools.

My own attempt at exegesis of "curation" (Shott 1996) questioned the value or relevance of most definitions and proposed instead that curation be defined as a ratio between two utilities: maximum and realized or expended. This definition makes curation a ratio-scale continuous variable that has an opposite no more than length or weight have opposites, and it locates curation at the level of tools, not assemblages or industries.

"Utility" may have several meanings (e.g., Shott 1996:269–271), but practically it signifies the amount of use that a tool can supply. This quantity can be measured, for instance, by material worked or energy transferred. Unfortunately, we cannot directly measure these quantities in archaeological objects. Yet we can estimate them indirectly because, like pencils, tools are used up by resharpening and therefore reduction. Reduction is our link to utility. (Collins (2008) showed that the form of tool edges influences amount of reduction experienced by tools and amount of utility that they deliver. This is an important complication that bears further experimental study, but I do not otherwise consider it here.)

Practically, therefore, maximum utility can be approximated as the greatest amount or degree of reduction that a tool can undergo, realized utility as the reduction (less than or equal to maximum utility) that it actually experiences. Both utilities, therefore, are based on the reducible mass or volume of tools. (The differences between size and form at first use and at discard give the degree of curation. Size and form at discard are simple matters of observation. However utility is defined, therefore, estimation requires knowing original size of specimens.) Here is the great theoretical importance of reduction: it provides the measure of utility that allows us to estimate the continuous variable of curation in prehistoric stone tools. Our chain of inference proceeds from measuring reduction to measuring realized utility to measuring, or at least estimating, curation.

Reduction/Curation Distributions

Every living person is described in part by his or her age, height, and other properties. One's age is simply a number. Age becomes important to demographers only when compiled across individuals in a population. Then demographers can compute measures of central tendency like mean and of dispersion like standard deviation. But demographers are not content with mean or other measures of central tendency. Instead, they study the frequency *distribution* of age in the population, which they characterize by its range and form. These properties of a population's age distribution reflect and therefore implicate social characteristics like wealth and public-health practices, economic characteristics like degree of industrial development, even natural factors like climate. For all of these reasons, Sweden and Sierra Leone, for instance, are apt to have very different age distributions of their living population and their age-at-death or mortality populations.

A common way to portray a mortality or age-at-death distribution is to plot age on the abscissa and cumulative survivorship on the ordinate. Cumulative survivorship ranges from 1 at the top to 0 at the bottom of the ordinate. It must equal to 1 when age = 0, so the cumulative distribution starts at maximum survivorship. Individuals begin to die by age 1 (in years or other time units). Perhaps few survive past early years, in which case the curve drops toward 0 (0% cumulative survivorship). Perhaps most individuals survive to relatively old ages until senescence or other factors gradually cause their demise, in which case the curve only falls

slightly from its maximum of 1.0 (100% survivorship), instead tracking horizontally across the range of ages attained. The cohort closes when the last member expires, which determines its span.

Figure 12.1 compares human cumulative survivorship in selected advanced industrial and underdeveloped populations. At a glance, it depicts the age-specific risk of mortality. Concave-upward distributions (e.g., the two nearer the lower left in Fig. 12.1) reflect high mortality at young ages. In contrast, convex-upward distributions reflect low mortality until advanced age (Fig. 12.1 upper right).

Distributions of course can be expressed graphically as survivorship curves. But the data that comprise the curves – the set of ordered age-at-death values that describe the cohort's aggregate demographic experience – also can be analyzed. One common way that demographers and, in different ways, engineers analyze such distributions is by fitting them to statistical models. Models themselves consist of parameters whose values are estimated from the empirical data. Models efficiently describe the form of distributions, permit distributions to be tested for their similarity or difference, and in some cases, identify the factors that produce their forms and scales. Models, that is, describe and can explain empirical distributions.

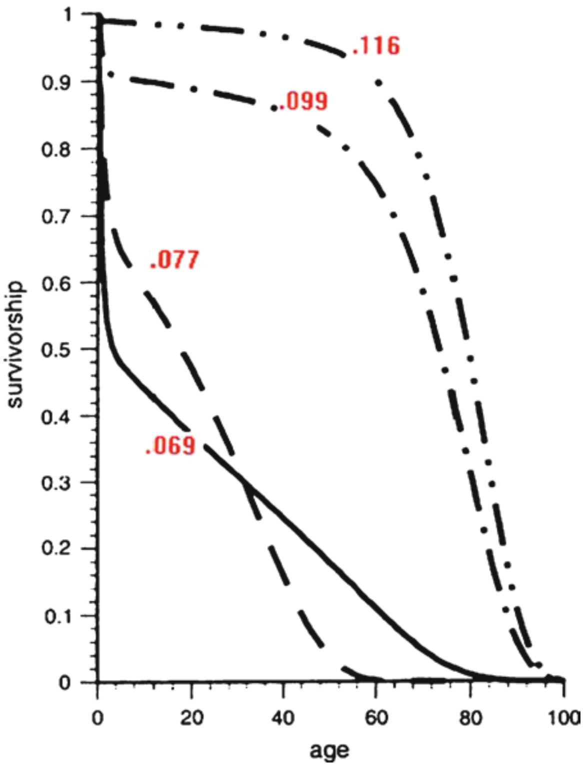

Fig. 12.1 Cumulative survivorship in selected human populations. Modified after, Shott and Sillitoe (2005, Fig. 5)

Demographers often fit age-at-death distributions to the Gompertz model of age-dependent mortality risk (e.g., Wood et al. 2002). Elaborations upon it like the Gompertz–Makeham model, which also takes account of age-independent risk, describe a population's age distribution efficiently in one or several parameters. Elsewhere (Shott and Sillitoe 2005), I argued that the Gompertz–Makeham *b* parameter was a measure of curation, because it varied positively with expected and realized lifespan in human demography and ethnoarchaeological artifact classes. Consistent with this argument, Gompertz–Makeham *b* rises as the distributions in Fig. 12.1 change from concave to convex. Engineers favor the Weibull model (Weibull 1951). Its β parameter has theoretical value, because engineers have determined through extensive experimentation and analysis that different ranges of its value implicate different factors: "burn-in" or high rates of failure in early use, chance, or attrition.

Similar logical and analytical methods apply in the study of reduction and curation. As above, in theory and concept, curation is not equivalent to use life or age. But similar analytical methods can apply to their study. Consider a class of stone tools. At first use, none has yet been reduced or its utility depleted. As the tools are used and reduced, they realize some fraction of their maximum utility. But some tools may be lost or abandoned after brief use, such that their ratio of realized to maximum utility – their curation degree or rate – is low. Others are used to greater degrees, hence are more heavily reduced and extensively curated. Age increases from birth to death. If curation can be expressed on a scale that rises with the amount of utility expended, the aggregate reduction/curation experience of sets of tools can be portrayed on cumulative-survivorship graphs like Fig. 12.1 and analyzed using model-fitting and other methods.

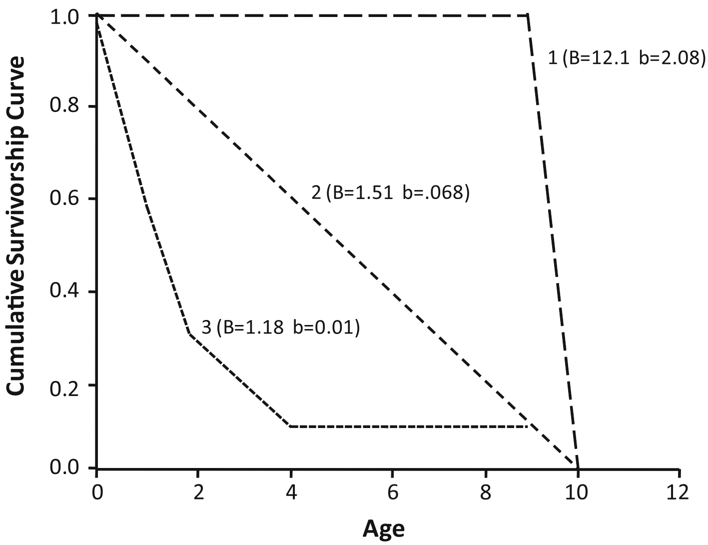

Fig. 12.2 Hypothetical cumulative-survivorship curves and associated parameters of the Weibull and Gompertz–Makeham models

For instance, Fig. 12.2 compares cumulative survivorship *qua* reduction/curation distributions in hypothetical lithic assemblages. Distribution 1 comprises tools, all of which survive to the point of maximum utility. At that point, all are depleted and discarded. The resulting curve is highly concave downward. In distribution 2, the first specimen is discarded at very low realized utility, the next at slightly more, and so on, until the last is discarded at the point of maximum utility and therefore maximum curation. Thus, specimens here have an equal probability of discard at all points along the range of curation (i.e., a constant risk of discard), so that distribution forms a straight descending line. In distribution 3, specimens mostly are discarded after slight use and reduction, well before maximum utility and reduction are reached; it is concave upward.

Curation distributions may seem esoteric, but reflect how the archaeological record formed (Shott and Sillitoe 2005). All else equal, for instance, tools that are only slightly curated will have high discard rates and so will accumulate in the archaeological record faster than will other tools. The first set of tools may be more abundant in the archaeological record, but their abundance does not owe to their popularity or frequency of use as much as to their low curation. Furthermore, if we can determine whether tools accumulated in the record by chance vs. by attrition (as, for instance, Weibull analysis determines), then their locations of discard may differ. Tools that fail by chance will accumulate broadly and perhaps randomly across the landscape. Tools that fail by attrition will accumulate where their depletion can be foreseen, for instance in residences. Finally and as above, measures of reduction and therefore curation correlated with occupation span in hunter–gatherer lithic assemblages (Surovell 2003).

In these and other ways, reduction/curation distributions have theoretical value, if only archaeologists take the slight trouble to compile, study, and analyze them. Yet curation distributions remain practically unknown in lithic analysis (cf. Shott 2008; Shott and Ballenger 2007; Shott and Sillitoe 2005). No faunal analysis is complete before determining death-age curves, whose form and scale distinguish hunting from attritional causes. No osteological analysis is complete before determining age-specific mortality because mortality distributions implicate diet, social complexity, and other cultural factors. In short, faunal analysis and paleodemography are incomplete without regard for the scale and form of mortality distributions. Lithic analysis is incomplete without regard for curation distributions. Therefore, a further goal of this study is to justify and advocate both the use of data distributions and methods like model-fitting and survival analysis commensurate with it.

Reduction and Model-Fitting

As above, reduction/curation distributions can be fitted to theoretical models. I emphasize Gompertz–Makeham and Weibull models. Model-fitting is the process of estimating model parameters from distributions, sometimes aided by plots of empirical observations against reduction/curation measures (e.g., the cumulative-survivorship plots discussed above).

Weibull and Gompertz–Makeham both are two parameter models. Weibull a is a scale (i.e., use life or longevity) parameter that estimates age-at-failure at the 63rd percentile of the distribution and β a shape parameter that implicates various causes of failure or discard (Shott and Sillitoe 2004). If $\beta < 1$, failure is by "burn-in," an engineering equivalent of high infant mortality; if $\beta = 1$, failure is by chance; if $\beta > 1$, failure is by attrition. Significant departure of β from 1 was gauged by maximum likelihood estimation (MLE) (Shott and Sillitoe 2004:344). Although $\beta > 1$ indicates attrition, it has no theoretical upper limit. Empirically, β can exhibit significant variation above 1 (e.g., Shott 2002; Shott and Sillitoe 2005). In theory, as β rises, the Weibull hazard function that reflects longer survivorship and steeper rising slope with age, i.e., items persisting for progressively longer lives until experiencing sharp rises in risk of death or failure. Therefore, higher β generally indicates greater reduction and higher curation. Gompertz–Makeham a also is a scale parameter, b a shape parameter that measures failure rate as a function of time. As above, Gompertz–Makeham b can be interpreted as curation rate, higher values indicating greater curation (Shott and Sillitoe 2005).

Weibull and Gompertz–Makeham parameters do not scale identically; the same data can yield different estimates for both parameters of the two models. Gompertz–Makeham parameters were estimated by MLE in WinModest (Pletcher 1999). Results were robust under sensitivity analysis. Weibull parameters were estimated using Dorner's (1999) spreadsheet method and George's (1991) MLE method. Dorner's and George's methods yield somewhat different estimates of Weibull parameters but identical inferences about causes of observed reduction/curation, and the several data sets form the same rank order in every case. Therefore, I report only George's parameter estimates.

Data

In an earlier example of curation analysis, North American Paleoindian fluted bifaces and endscrapers had different characteristic cumulative-survivorship curves and failure distributions (Shott and Sillitoe 2004:350–352). Biface discard was governed by chance, no surprise considering that bifaces ("points") are thin for their size and are subjected to myriad physical stresses from striking objects at high speeds. Shott and Sillitoe studied very small assemblages, so their conclusion requires confirmation in larger samples.

Here, I use much larger samples of bifaces from two successive Paleoindian phases, Gainey (circa 11,000 rcybp) and Parkhill (circa 10,900–10,500 rcybp) in the mid-western USA, culled from the published literature. Some specimens are from large assemblages customarily recognized as "sites," even, in cases, the aggregation "sites" often thought to characterize the Paleoindian archaeological record (cf. Shott 2004). Many, however, are commonly called "isolates," which are either true isolates or the only discovered or reported (perhaps because highly recognizable and esteemed by collectors) artifacts among those from "sites" because of vagaries of sampling.

This data set comprises tools probably discarded in many contexts for many reasons. I used about 380 Clovis–Gainey bifaces and about 80 Barnes bifaces of Parkhill affinity from assemblages mostly in the eastern Midwest. (The difference in sample sizes roughly reflects the difference in abundance, to judge from published sources.)

For comparison, I also used Hunzicker's (2005) experiment that involved 25 Folsom biface replicas fired into the rib cages of slaughtered cows in order to study the functionality, probability of failure, and breakage pattern of specimens hafted as dart points. Hunzicker bifaces might document only modest curation, because most failed by accidental breakage in use independent of their number of previous uses or degree of rejuvenation and reduction experienced. However, a small subset of Hunzicker specimens ($n = 7$) were used and reduced extensively but did not fail by accident in five or more uses. I treated these as a separate group that represented high curation of fluted bifaces.

Hunzicker specimens were retired from analysis when they fractured during use. In archaeological context, therefore, these bifaces would be recovered in pieces. All archaeological specimens analyzed were recovered whole. Yet their size, dimensions, and allometry at discard are directly comparable to Hunzicker's experimental bifaces at the various intermediate stages between first use and utter depletion that the latter represent. Because they were measured before each instance of use, experimental bifaces yield precisely identical data to archaeological specimens; their subsequent fracture is irrelevant to analysis. Thus, Hunzicker's experimental bifaces might comprise a baseline against which to compare Midwestern Paleoindian bifaces. If the latter are extensively curated, their model parameters might differ from those for most of Hunzicker's experimental bifaces, but might approximate those for Hunzicker's subset of heavily used and reduced bifaces.

Reduction in Bifaces

Hafted bifaces fracture readily, whether used as projectiles like dart or arrow point, or as knives (e.g., Beck 1995). Indeed, breakage and subsequent rejuvenation are central to recent models of Folsom biface use (Ahler and Geib 2000; cf. Buchanan 2006) and fluted biface design and rejuvenation in northeastern North America (Ellis 2004:216–217). Reduction effects are documented for stemmed bifaces generally (Andrefsky 2006, 2008) and for a series of mid-Holocene stemmed forms in eastern North America (Granger 1978; Hoffman 1985) and South America (Cardillo 2005; Iriarte 1995; Suárez 2004). Wheat (1974) proposed reduction effects or trajectories for early Holocene San Jon bifaces in the American Southwest, and more detailed studies document reduction trajectories in southeastern Dalton bifaces of broadly similar age (Shott and Ballenger 2007). More detailed allometric analysis also identified reduction effects in Debert fluted bifaces from the Canadian Maritimes (Ellis 2004) and Paleoindian Folsom bifaces from the southern Plains (Buchanan 2006). Mid-Holocene Argentine lanceolate bifaces varied in both “robusticity” (width × thickness/length) and an index of rejuvenation expressed simply as length divided by thickness,

both as a function of resharpening (Cardillo 2005:81). Suárez (2004:33) showed a sequence of slightly changing stem size and form and greatly changing blade size and form, along with decreasing angularity or definition of shoulders in Uruguayan Fluted Fishtail points. These studies mostly used orthogonal dimensions or geometric characteristics of specimens, although face angle (the angle formed between base and side) was related to degree of reduction at Debert (Ellis 2004:215–217).

Hunzicker's (2005) study provided a rich source of data on reduction effects in bifaces. Specimens were measured before first use. Most suffered damage in the course of the experiment, although their service lives (i.e., number of shots) varied. Most damage was confined to tips (Hunzicker 2005:41, Fig. 7). If damage was not catastrophic, bifaces were rejuvenated by careful resharpening (Hunzicker 2005:27–29). The effect was to shorten the bifaces and reduce their mass but to alter other dimensions little, and thereby to change shape and the proportions among dimensions.

Hunzicker's experimental design supplies control data, because specimen metrics, ratios, and proportions are known or can be calculated for each cycle of use and resharpening. Shott et al. (2007) examined them for reduction in length and change in proportions that specimens experienced in each cycle, in the process comparing several reduction measures such as simple ratios of length to thickness (LT), mass to thickness (MT), and area to thickness (AT). All patterned significantly with degree of reduction measured independently by mass loss and number of rejuvenations. Among them, LT patterned most strongly and clearly. LT is a simple ratio that previous studies also found to be a useful reduction measure (Iriarte 1995; Cardillo 2005). Wilson and Andrefsky (2008:92–94) also documented allometric loss of both surface area and mass as reduction progressed, although effects were disproportionately great in the earliest reduction episodes. Therefore, I use LT as an allometric measure of degree of reduction.

LT thus measures how much reduction a biface experienced. But curation is measured as a ratio between realized and maximum utility, which requires knowing or estimating original size before reduction. A tool's size at discard is a simple matter of measurement, via LT in this case. But knowing how much it was reduced in use requires knowing original size. For fluted bifaces, I estimated original size from dimensions of Paleoindian fluted bifaces found in Midwestern or other caches (Anderson and Tiffany 1972; Gramly 1999). Cache bifaces were longer than analyzed specimens found at occupational sites, but not consistently longer in other dimensions of blade or haft. Thus, mean LT among cache specimens was treated as the maximum value before use and reduction, hence an estimate of a tool's condition before use where no utility (sensu Shott 1996) yet is expended.

Observed LT among archaeological and experimental specimens thus is a measure of their realized utility. The ratio of observed LT to maximum LT yields an index that varies between 0 and 1, where higher values indicate less realized utility and thus lower curation. I subtracted the result from 1 such that:

$$\frac{\text{Reduction}}{\text{curation}} = 1 - \left(\frac{\mathrm{LT}_{\mathrm{OBS}}}{\mathrm{LT}_{\mathrm{MAX}}} \right),$$

so that more reduced specimens have higher values equivalent to higher curation or greater age.

Analysis

With its theoretical and methodological preconditions met, it is possible to use reduction indices to measure curation. Analysis of LT in Paleoindian bifaces is summarized in Tables 12.1 and 12.2. Figures 12.3 and 12.4 show cumulative survivorship for Hunzicker and archaeological bifaces, respectively.

All Hunzicker specimens combined produce a Weibull β parameter that rounds to 1.0, indicating failure by accident. This result agrees perfectly with expectations: Hunzicker specimens failed by chance, the accident of what part of a target they struck, at what speed and angle. The corresponding cumulative-survivorship curve is nearly linear (Fig. 12.3), approximating distribution 2 in Fig. 12.2. At the opposite extreme, long-lived Hunzicker bifaces yield a very high β-value (Table 12.1) and convex survivorship curve (Fig. 12.3), indicating an advanced state of curation. As suspected, Hunzicker's experimental control and specimens provide the baseline against which to compare other data.

Paleoindian data yield β-values that indicate failure by attrition. These tools wore out; they did not fail by accident. Cumulative survivorship curves are similar, and modestly convex upward (Fig. 12.4). Surprisingly, Gainey bifaces yield a lower β than do Barnes bifaces (Table 12.2). At face value, then, Barnes bifaces are somewhat more, not less, curated than Gainey ones, contra common belief among Paleoindian archaeologists including me. Gainey and Barnes bifaces have nearly identical Gompertz–Makeham b-values. Again, long-lived Hunzicker specimens have by far the highest value, but all Hunzicker bifaces combined have a slightly higher b-value than any archaeological set.

Therefore, Gainey and Barnes bifaces are only ambiguously more reduced and, by extension, curated than are experimental Folsom specimens that failed by accident, but they are much less curated than the longest-lived experimental specimens. If the aggregate Midwestern distributions imply attrition, they do not suggest heavy attrition or particularly high curation rates.

Table 12.1 Weibull and Gompertz–Makeham parameter estimates for Hunzicker's Folsom replicas

	Weibull		Gompertz–Makeham	
	α	β	a	b
All combined	0.34	1.00 (=1)	0.003	0.081
Long-lived	0.47	8.31 (>1)	0.0003	0.185

Long-lived specimens are those that survived five or more uses ($n=7$) (parentheses following Weibull β-values indicate similarity or difference from a value of 1)

Table 12.2 Weibull and Gompertz–Makeham estimates for Gainey and Barnes fluted bifaces

	Weibull		Gompertz–Makeham	
	α	β	a	b
Gainey	0.36	1.90 (>1)	0.004	0.072
Barnes	0.36	2.64 (>1)	0.004	0.073

Parentheses following Weibull β-values indicate similarity or difference from a value of 1

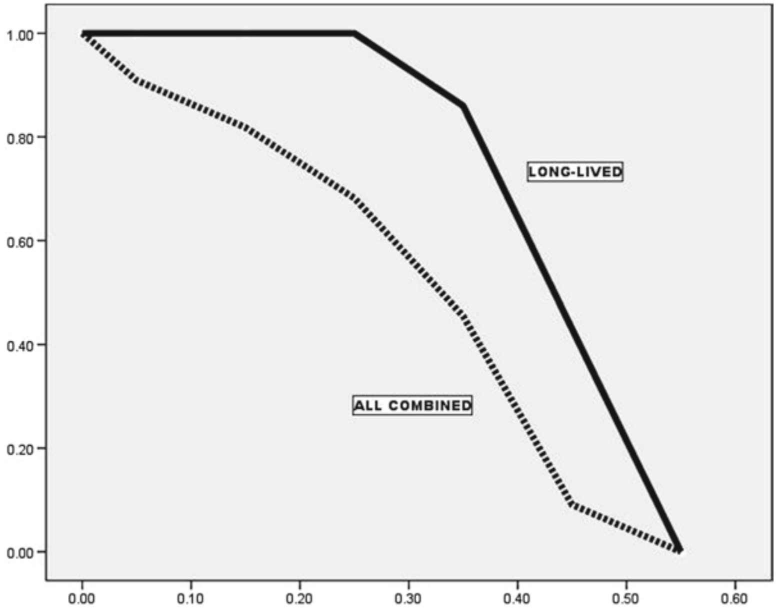

Fig. 12.3 Cumulative survivorship in Hunzicker bifaces

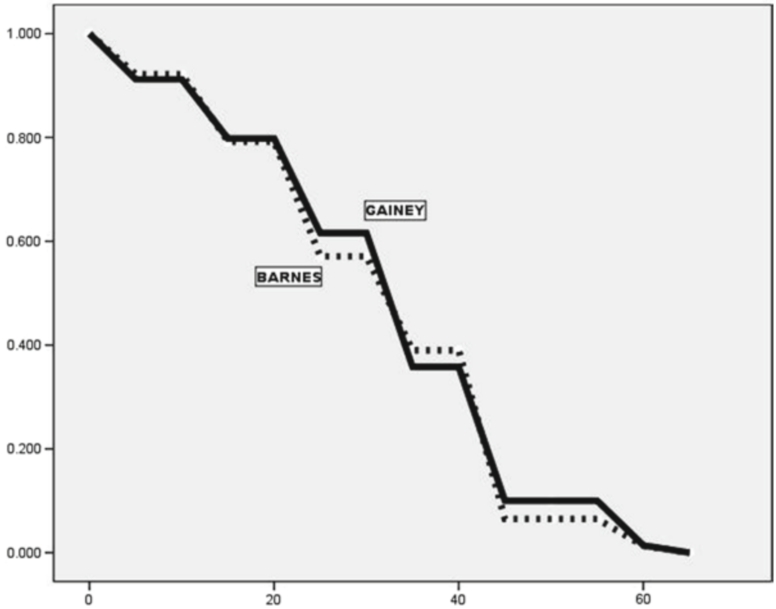

Fig. 12.4 Cumulative survivorship in Gainey and Barnes bifaces

Implications of Reduction Analysis

Analysis of reduction/curation distributions has implications beyond curation itself. All else equal, for instance, rate of curation is directly inverse to rate of discard. Under those circumstances, where curation rates are higher discard rates necessarily are lower and fewer specimens accumulate in the archaeological record. One surprising conclusion is that Midwestern Paleoindian bifaces were not heavily curated. The smaller number and much lower density of fluted bifaces in western compared to eastern North America are well known and much pondered. Most proposed explanations stress the higher environmental productivity of the late Pleistocene East. By implication, the greater abundance of fluted bifaces is assumed to reflect correspondingly higher Paleoindian populations. That certainly is possible, but at least part of the difference in abundance of fluted bifaces may owe to differences in curation and, by extension, discard rates. Even this possible explanation is merely proximate because it begs the higher question of what caused the difference in rates. But it has the virtue of at once considering formation processes in general explanations and locating the cause in factors besides population alone.

Another implication concerns transmission modes and rates, a growing concern in an archaeology increasingly oriented to evolutionary explanations. All else equal again, the longer that tools were used and therefore the less often they were discarded, the lower the production rate of replacements. This rate necessarily affects the rate of transmission of received variants and may affect transmission mode as well.

Scanning

To date, most reduction measurement is grounded in orthogonal dimensions (e.g., length, width) and ratios among them. This is neither bad nor surprising; orthogonal dimensions are perfectly legitimate ways to measure things. But rapid innovations in scanning technology hold great promise to improve both the efficiency and accuracy of tool measurement generally and reduction measurement in particular. That potential already is illustrated in the case of two-dimensional scanning (e.g., Buchanan 2006; Castiñeira et al. 2007). Three-dimensional scanning now is becoming practical and may prove even more valuable in the future.

Conclusion

The above are mere examples of reduction analysis and the fitting of reduction/curation distributions to mathematical models. As research continues, we must consider challenges and problems. There always is the empirical problem of more data, which bears no more than passing mention here. More significant are methodological problems.

We must learn more about the consistency of different reduction measures and the distributions that result from them. If the same tools yield significantly different distributions using different reduction measures, then we must determine the most valid measures. There is also the question of measurement scale of input data. Weibull often is applied to very small data sets in which each tested specimen's time-to-failure can be input. But stone-tool assemblages, like human and other populations, often are large enough that input data on reduction must be pooled. The number and width of intervals chosen may influence results, especially in fitting to Gompertz–Makeham. Again, we need more study of possible effects before this approach to reduction analysis becomes standardized.

Besides the validity of measures, we must consider additional mathematical models. Demographic models were designed for common patterns of mortality in human and animal populations. Animals and stone tools do not survive for the same lengths of time, so of course their mortality or curation distributions differ in scale. Scale parameters and relative reduction/curation measures control for such differences. (Various reduction measures also may differ in range and scale; presumably, scale parameters can measure and thereby control for this variation.) More significant are differences in the shape or form of distributions. Demographic models assume low mortality either from birth or inception or after an initial period of relatively high risk, until late stages of life. Accordingly, a typical hazard distribution for humans and other animals is roughly U-shaped. There is no reason to assume that the distribution of risk of failure is similar in stone tools or other archaeological objects. Other models may be more suitable.

The reduction thesis reflects how assemblages form and what they mean. In stone tools, reduction is linked to curation. Reduction can be measured. Using engineering and demographic methods, reduction indices in turn can be used to measure curation. That concept, long an influential but ambiguous concept in lithic analysis and hunter–gatherer archaeology, now can be measured and distributions of its value analyzed for the information they provide. Methodological challenges remain before reduction analysis becomes a standard tool of the trade in lithic analysis. But there is no reason to ignore the potential that reduction and hence curation analysis holds to broaden the scope of cultural inference from sparse archaeological remains.

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References

Ahler, S. and Geib, P., 2000. Why flute? Folsom point design and adaptation. *Journal of Archaeological Science* 27: 799–820.

Anderson, A. and Tiffany, J., 1972. Rummells-Maske: A Clovis find-spot in Iowa. *Plains Anthropologist* 17: 55–58.

Andrefsky, W., 2006. Experimental and archaeological verification of an index of retouch for hafted bifaces. *American Antiquity* 71: 743–757.

Andrefsky, W. (ed.), 2008. *Lithic Technology: Measures of Production, Use and Curation*. Cambridge University Press, Cambridge, UK.

Barton, C.M., Olszewski, D. and Coinman, N., 1996. Beyond the graver: Reconsidering burin function. *Journal of Field Archaeology* 23: 111–126.

Beck, C., 1995. Functional attributes and the differential persistence of Great Basin dart forms. *Journal of California and Great Basin Anthropology* 17: 222–243.

Binford, L., 1973. Interassemblage variability: The Mousterian and the 'functional' argument. In *The Explanation of Culture Change: Models in Prehistory*, edited by C. Renfrew, pp. 227–254. Duckworth, London.

Blades, B., 2003. End scraper reduction and hunter-gatherer mobility. *American Antiquity* 68: 141–156.

Buchanan, B., 2006. An analysis of Folsom projectile point resharpening using quantitative comparisons of form and allometry. *Journal of Archaeological Science* 33: 185–199.

Cardillo, M., 2005. Explorando la Variación en las Morfologías Líticas a Partir de la Técnica de Análisis de Contornos: El Caso de las Puntas de Proyectil del Holoceno Medio-Tardío de la Puna de Salta (San Antonio de los Cobres, Argentina). *Revista Werken* 7: 77–88.

Castiñeira, C., Cardillo. M., Charlin, J., Fernicola, J. and Baeza, J., 2007. Análisis morfométrico de los Cabezales Líticos "Cola de Pescado" del Uruguay. Paper presented at the Primer Congreso Latinoamericano de Arqueometría, Buenos Aires.

Collins, S., 2008. Experimental investigations into edge performance and its implications for stone artefact reduction modelling. *Journal of Archaeological Science* 35: 2164–2170.

De Bie, M., 2007. Benefiting from refitting in intra-site analysis: Lessons from Rekem (Belgium). In *Fitting Rocks: Lithic Refitting Reexamined*, edited by U. Schurmans and M. De Bie, pp. 31–44. BAR International Series 1596, Archaeopress, Oxford.

Dibble, H., 1987. The interpretation of Middle Paleolithic scraper morphology. *American Antiquity* 52: 109–117.

Dorner, W., 1999. Using MicroSoft Excel for Weibull analysis. *Quality Digest* 19: 33–38.

Ellis, C., 2004. Understanding 'Clovis' fluted point variability in the Northeast: A perspective from the Debert Site. *Canadian Journal of Archaeology* 28: 205–253.

Eren, M. and Prendergast, M., 2008. Comparing and synthesizing unifacial stone tool reduction indices. In *Lithic Technology: Measures of Production, Use and Curation*, edited by W. Andrefsky, pp. 49–85. Cambridge University Press, Cambridge.

Eren, M., Dominguez-Rodrigo, M., Kuhn, S., Adler, D., Le I. and Bar-Yosef, O., 2005. Defining and measuring reduction in unifacial stone tools. *Journal of Archaeological Science* 32: 1190–1201.

Frison, G., 1968. A functional analysis of certain chipped stone tools. *American Antiquity* 33: 149–155.

George, L., 1991. Maximum likelihood estimation of Weibull parameters. Electronic document, http://home.comcast.net/~pstlarry/BaikoMan.htm, accessed 20 January 2008.

Gramly, R., 1999. *The Lamb Site: A Pioneering Clovis Encampment.* Persimmon Press, Buffalo, NY, USA.

Granger, J.E., 1978. *Meadowood phase settlement pattern in the Niagara Frontier Region of Western New York State*. University of Michigan Museum of Anthropology, Anthropological Paper No. 65. Ann Arbor, MI, USA.

Grimes, J. and Grimes, B., 1985. Flakeshavers: Morphometric, functional and life-cycle analyses of a Paleoindian unifacial tool class. *Archaeology of Eastern North America* 13: 35–57.

Hayden, B., 1977. Stone tool functions in the western desert. In *Stone Tools as Cultural Markers: Change, Evolution, and Complexity*, edited by R. Wright, pp. 178–188. Australian Institute of Aboriginal Studies, Canberra.

Hiscock, P. and Attenbrow, V., 2003. Early Australian implement variation: A reduction model. *Journal of Archaeological Science* 30: 239–249.

Hoffman, C.M., 1985. Projectile point maintenance and typology: Assessment with factor analysis and canonical correlation. In *For Concordance in Archaeological Analysis: Bridging Data*

Structure, Quantitative Technique, and Theory, edited by C. Carr, pp. 566–612. Westport Press, Kansas City, MO.

Holdaway, S., McPherron, S. and Roth, B., 1996. Notched tool reuse and raw material availability in French Middle Paleolithic sites. *American Antiquity* 61: 377–387.

Hunzicker, D., 2005. *Folsom Hafting Technology: An Experimental Archaeological Investigation into the Design, Effectiveness, Efficiency and Interpretation of Prehistoric Weaponry*. Unpublished M.A. Thesis, Department of Museum and Field Studies, University of Colorado, Boulder.

Iriarte, J., 1995. Afinando la Puntería: Tamaño, Forma y Rejuvenecimiento en las Puntas de Proyectil Pedunculadas del Uruguay. In *Arqueología en el Uruguay: 120 Años Despues*, edited by M. Consens, J.M. López Mazz and M. del Carmen Curbelo, pp. 142–151. Editorial SURCOS, Montevideo.

Kuhn, S., 1990. A geometric index of reduction for unifacial stone tools. *Journal of Archaeological Science* 17: 583–593.

Mayr, E., 1991. *One long argument: Charles Darwin and the genesis of modern evolutionary Thought*. Harvard University Press, Cambridge, USA.

Morrow, J., 1996. End scraper morphology and use-life: An approach for studying Paleoindian lithic technology and mobility. *Lithic Technology* 22: 70–85.

Neeley, M. and Barton, C.M., 1994. A new approach to interpreting late Pleistocene microlith industries in Southwest Asia. *Antiquity* 68: 275–288.

Pelcin, A., 1996. *Controlled Experiments in the Production of Flake Attributes*. Ph.D. dissertation, University of Pennsylvania, University Microfilms, Ann Arbor, MI, USA

Pletcher, S.D., 1999. *WINMODEST Documentation*. Unpublished ms. on file, Baylor University Dept. of Medicine, Houston, TX, USA.

Sahnouni, M., Schick K. and Toth, N., 1997. An experimental investigation into the nature of faceted limestone "spheroids" in the early Palaeolithic. *Journal of Archaeological Science* 24: 701–713.

Shott, M., 2008. Lower Paleolithic industries, time, and the meaning of assemblage variation. In *Time in Archaeology: Time Perspectivism Twenty Years Later*, edited by S. Holdaway and L. Wandsnider, pp. 46–60. University of Utah Press, Salt Lake City, UT.

Shott, M., 2007. Recent advances in stone-tool reduction analysis: A review for Brazilian archaeologists. In *Das Pedras aos Homens: Tecnologia Lítica na Arqueologia Brasileira*, edited by L. Bueno and A. Isnardis, pp. 243–267. Argumentum Editora, Belo Horizonte, Minas Gerais.

Shott, M., 2005. The reduction thesis and its discontents: Review of Australian approaches. In *Lithics 'Down Under': Australian Perspectives on Lithic Reduction, Use and Classification*, edited by C. Clarkson and L. Lamb, pp. 109–125. British Archaeological Reports International Monograph Series 1408, Archaeopress, Oxford.

Shott, M., 2004. Hunter-gatherer aggregation in theory and evidence: The North American Paleoindian case. In *Hunter-Gatherers in Theory and Archaeology*, edited by G. Crothers, pp. 68–102. Southern Illinois University, Center for Archaeological Investigations, Carbondale, IL.

Shott, M., 2002. Weibull estimation of use-life distribution in experimental spear-point data. *Lithic Technology* 27: 93–109.

Shott, M., 1996. An exegesis of the curation concept. *Journal of Anthropological Research* 52: 259–280.

Shott, M., 1995. How much is a scraper? Curation, use rates and the formation of scraper assemblages. *Lithic Technology* 20: 53–72.

Shott, M. and Ballenger, J., 2007. Biface reduction and the measurement of Dalton curation: A Southeastern case study. *American Antiquity* 72: 153–174.

Shott, M. and Sillitoe, P., 2004. Modeling use-life distributions in archaeology using new Guinea Wola ethnographic data. *American Antiquity* 69: 336–352.

Shott, M. and Sillitoe, P., 2005. Use life and curation in New Guinea experimental used flakes. *Journal of Archaeological Science* 32: 653–663.

Shott, M. and Weedman, K., 2007. Measuring reduction in stone tools: An ethnoarchaeological study of Gamo hidescraper blades from Ethiopia. *Journal of Archaeological Science* 34: 1016–1035.

Shott, M., Hunzicker, D. and Patten, B., 2007. Pattern and allometric measurement of reduction in experimental Folsom bifaces. *Lithic Technology* 32: 203–217.

Shott, M., Bradbury, A., Carr, P. and Odell, G., 1999. Flake size from platform attributes: Predictive and empirical approaches. *Journal of Archaeological Science* 27: 877–894.

Suárez, R., 2004. Paleoindian components of Northern Uruguay: New data on early human occupations of the late Pleistocene and early Holocene. In *Where the South Winds Blow: Ancient Evidence for Paleo South Americans,* edited by L. Miotti, M. Salemme and N. Flegenheimer, pp. 29–36. Texas A&M University, College Station.

Surovell, T., 2003. *Behavioral Ecology of Folsom Lithic Technology*. Ph.D. dissertation, University of Arizona, University Microfilms, Ann Arbor, MI, USA.

Tindale, N., 1965. Stone implement making among the Nakako, Ngadadjara and Pitjandjara of the Great Western Desert. *Records of the South Australian Museum* 15: 131–164.

Truncer, J., 1990. Perkiomen points: A study in variability. In *Experiments and Observations on the Terminal Archaic of the Middle Atlantic Region*, edited by R. Moeller, pp. 1–62. Archaeological Services, Bethlehem, CT.

Weibull, W., 1951. A statistical distribution function of wide applicability. *Journal of Applied Mechanics* 18: 293–297.

Wheat, J., 1974. Artifact life histories: Cultural templates, typology, evidence and inference. In *Primitive Art and Technology*, edited by J. Raymond, B. Loveseth and G. Reardon, pp. 7–15. University of Calgary, Department of Archaeology, Calgary.

Wilson, J. and Andrefsky, W., 2008. Exploring retouch on bifaces: Unpacking production, resharpening, and hammer type. In *Lithic Technology: Measures of Production, Use and Curation*, edited by W. Andrefsky, pp. 86–105. Cambridge University Press, Cambridge.

Wood, J.W., Holman, D., O'Conner, K. and Ferrel, R., 2002. Models of paleodemography. In *Paleodemography: Age Distributions from Skeletal Samples*, edited by R. Hoppa and J. Vaupel, pp. 129–168. Cambridge University Press, Cambridge.

Chapter 13
The Future of Lithic Analysis in Palaeolithic Archaeology: A View from the Old World

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Abstract Archaeology has to rise to the challenge of projecting itself, accommodating new relationships with disciplines such as evolutionary psychology and anthropology, primatology and genetics. This task requires a reorganisation of approach, so that archaeology does not seem to take purely minimalist views, based simply on the current record of preserved finds. Early archaeology in the Old World divides overall into the dynamics of big evolutionary outlines, and scenarios of local detail. Both are equally important in building a record. The first is more subject to major changes of perspective, and the second offers more continuity in its analytical techniques. The chapter explores recent developments in Palaeolithic archaeology as hints of changes to come.

Paleolithic Archaeology – centrally depending on the analysis of stone tools which is our concern – is to all Palaeolithic archaeologists the indispensable way of looking at the past. People who do not partake of it are missing the most essential part of human experience, the shaping of humanity. But more than usually at present, we need to show the World that this is so (or the World may not notice).

Stone Age archaeology – the archaeology of the more distant human past – was shaped as an idea by Christian Thomsen (1836), from the finds of Denmark, and began to find its time depth with the work of Boucher de Perthes 150 years ago (Boucher de Perthes 1864; Gamble and Kruszynski 2009; Gowlett 2009). Since then it has constructed a huge picture and from time to time we need to step back from it, to try and look forward. Glynn Isaac did so in 1971, in a competition organised by *Antiquity* (*Whither archaeology?* Reputedly Isaac who had spelling difficulties headed it "Wither Archaeology"). It is tempting to begin from that paper (Isaac 1971) so as to survey the next generation's progress across the Old World, but I would rather hold its conclusions for comparison at the end and make a fresh start now. But we

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should note here the catalytic role of Isaac's other ideas (e.g., Isaac 1969, 1972), and the significance of his close association with David Clarke, one of the most influential figures in the New Archaeology. This volume in part marks the 40th anniversary of David Clarke's *Analytical Archaeology* and by chance the time of writing marks also another anniversary – 50 years since the Leakeys recovered the association of stone tools and an early hominid at Olduvai Gorge (Leakey 1959). From their finds, Isaac drove forward the idea that changing timescales had major implications (Isaac 1969, 1972), and along with Clarke he tackled another point that we can make thematic – the importance of rates of change. Stewart (1995: 55) emphasises the broad mathematical principle established by Newton that "laws are formulated as equations that relate not to the physical quantities of primary interest but the rates at which those quantities change with time".

In Palaeolithic research, we seem to have two main aims in looking at this past. One is to carry out the duty of making a record of each and every bit, as in history. This mapping is akin to wallpapering each bit of space and time, with a record that consists largely of stone tools, but also of their contexts. Preservation permitting, everywhere has the potential for this detail. This approach is similar to that of regional local history – charting the *evénéments* of Braüdel (Bintliff 1991, 2003). It implies that from the start all events are equal, and no one's actions are more or less important. In archaeology, it can lead to a search for the individual as such (Gamble and Porr 2005).

Our other major approach is geared to mapping out the dynamics of human evolution, to tackling the biggest picture. Many Palaeolithic archaeologists have this aim. They are more interested in the problems of human evolution than the archaeological record itself. In most cases, they tackle a slice of the whole: an inspection of the pages of *Evolutionary Anthropology* or *Current Anthropology* shows that mostly we tend to focus on early human origins or modern human origins, one at a time, but the big frame is the goal. Many of the papers in this book clearly also have this goal, despite their equal focus on detail and methodology.

It is worth adding that just as Braüdel (1972) sketched out a series of historical levels, so had Clarke and Isaac and colleagues in their writings on culture groups and technocomplexes (Clark et al. 1966; Clarke 1968; Isaac 1972). Their scale of entities forms a bridge between the large and small pictures.

The detailed approach is of course at least as valid as the major evolutionary one, and it is going to soak up a huge amount of the day-to-day efforts. Indeed the larger picture must be built up from its blocks. If you are studying the Upper Palaeolithic in Italy or the LSA in Namibia, the questions are different, but not less important: documentation of each relevant aspect – the building of a full palaeoecological and sociotechnical picture – is vital, whether it is at Olduvai or Etiolles.

Big Picture Dynamics

I will concentrate first on this bigger picture, which actually embraces all the human revolutions (Gamble 2007; Gowlett 2009a), except those of agriculture and civilization. What was it, and how has it changed?

A generation ago, the timescale of archaeology was freshly set by Olduvai Gorge, to about 1.8 million years. Omo broke the two million year barrier. The associations were with early *Homo* (*Homo habilis*) (Leakey 1978). Further back in time was the idea of more primitive australopithecines, and then… a blank. The blank added an exotic sense of mystery, but it did not really matter, because the golden egg of culture started with the early tools. Further back somewhere were early apes, as at Rusinga or Fayum. As comparative framework, chimpanzees were nowhere. Savanna was everywhere – baboons dominated the field of modelling. Some of these views have been lost (and the task is to see not just what has replaced them, but what pointer that is to what will come next).

Were the problems solved? It seems more, as Arber (1985) shows, that problems in science are often not directly solved, but tackled until eventually some development leads to them being bypassed. It is sometimes said that major new ideas have a 15-year timescale before they rejoin the mainstream. In that case, we have been through several phases. In palaeoanthropology, we might have the Leakey effect 1960–1975; then the Isaac ideas – 1970–1985. The Binford middle rangeism was dominant 1980–1995 (see e.g. Binford 1983; Isaac 1969, 1972; Leakey 1978). David Clarke's version of the New Archaeology had wider implications, but its greatest influence was in the same years as Isaac's. There has been less postprocessualism, which has had indirect effects in the Palaeolithic. Arguably, we have been in our present "modern" phase since the late 1990s, without any one dominant paradigm, and perhaps we should be looking for a new "-ism".

Newer Ideas

The current set of ideas represents a definite departure – they crystallised with the new millennium. They include the new importance of primatology, which through chimpanzee activities brings a new life to the stone ages. Then there is a vista opened up by the new suite of very early hominids (*Orrorin*, *Sahelanthropus* and *Ardipithecus*). From 2000 too came a deep extension of declared interests in early modern humans – a perspective of 300,000 rather than 50,000 years (McBrearty and Brooks 2000; Barham 2002). Equally or more important is the extension of a genetic framework, with the first Neanderthal DNA (from 1997) paving the way to a Neanderthal genome project, which will fundamentally alter our understanding of the last million years (i.e. the time back to a common ancestor of Neanderthals and modern humans) (Green et al. 2006; Krause et al. 2007; Krings et al. 1997). Then there is the intervention of evolutionary psychology, which paints broad brush across the past, projecting in interpretations seemingly without a direct need for archaeology. As long ago as 1997, I noted that archaeology needs to come to terms with the power of the new disciplines (Gowlett 1997). It cannot just operate on its own. If it tries to do so, it will be bypassed.

The New Developments

These new phenomena have done much to reshape the subject area. As hinted, we can take a modern phase from 2000, and try to follow it through. The changing big picture of human evolution seems almost equally driven by the several developments. The fossil record is key, because nothing else would give us views of brain size, teeth, and bipedalism. Very gradually, I would predict, it will link up with genetic insights. That is, science will begin to know the genetic basis underpinning particular characters – and then triangulating from the human, chimpanzee, and Neanderthal genomes, it may become possible to fix the points at which certain evolutionary changes occurred. We also know that (apart from the major component of drift) the genetic changes are largely driven by behavioural changes, which of course are partly documented by the very artefacts we study.

In the near future the preoccupation will be with understanding the Neanderthals as Neanderthals. Eventually, however, triangulation from moderns and Neanderthals should get us close to comprehending the genome of *Homo erectus*, at the head of the two diverging lines about one million years ago. That is a time of major change – with a *heidelbergensis*-like *Homo* perhaps appearing widely before the final divergence, and almost certainly being linked with some of the precocious events visible in the Acheulean (e.g. at Atapuerca or Bodo). The genetics is clearly a two-edged sword, if not used with great care. Authors have assumed that signs of a population bottleneck in humans were related to a recent squeeze, perhaps linked with the Toba eruption at 70,000 years ago (Ambrose 1998). Then similarly the discovery that the *FOXP2* gene had a mutated form in modern humans was immediately linked with a recent "language event" in modern humans. The discovery that Neanderthal variation has similar narrow bandwidth, and that they too had our version of *FOXP2* (Krause et al. 2007) completely alters such interpretations, and moves the developments way beyond the range of Toba or recent language.

Such readjustments tell us not just about themselves, but about the likely need for many similar corrections of current views, especially those reached rather hastily. Even so, the corrections too are coming from genetic evidence, and if we compare 1989 with 2009, then 2029 should have a juicy menu on offer.

More fare will certainly come from the hominin remains. Wang and Crompton's (2004) analyses of hominin carrying show the kind of work that can be done, that relates to artefacts, as do Trinkaus' longer-standing explorations of Neanderthal life style (see Trinkaus and Shipman 1993). In a similar vein, Aiello and Dunbar (1993), Aiello and Wheeler (1995), and Aiello and Key (2002) are all working towards what *must* have happened in some particular way, as in the expensive tissue hypothesis, which asserts that we could not have acquired our large expensive brains without reduction in other key tissue, with further knock-on implications.

The same can be said for evolutionary psychology, although it is anathema to some archaeologists. As with the genetics, it sometimes marches too confidently across areas which have already been explored by archaeologists, and whose data strongly point towards other views.

The importance of social factors is not new, but the evolutionary psychology gives it a new focus beyond the "ordinary" social archaeology. Indeed the Machiavellian intelligence and Social Brain ideas make a direct link with primatology, which also enters the picture through studies of primate material culture (Byrne and Whiten 1988; Dunbar 1998, 2003; Dunbar et al. 2010; Gowlett 2009b; Lycett et al. 2009; Whiten et al. 2009). The Social Brain makes plain that there were always larger worlds than archaeology can see directly (Dunbar et al. 2009). So when somebody, like Gargett (1989, 1999), could say that a body might be disposed of just because it was in the way or smelled, we can counter that brain evidence suggests that these hominins had four or five levels of intentionality and that they would fully understand what they were doing. We can look to other archaeological signs – such as the spatial separation of infants and adult burials – and say that this fits. Social brain tells us about changes in group sizes, and also to expect a long and gradual emergence of language as a replacement for primate grooming. Where can it take us next? The main thing may be for archaeology to keep working through the ideas. We need to articulate more fully in our theory that "WYSWTW" (What you see is what there was) is a fundamentally unsatisfactory approach. To say "We cannot believe in x or y until we have seen it at least three times" is no longer a good approach, if other disciplines will say "it should be there and you archaeologists just did not find it."

Part of an answer can come from a fuller exploration of sampling issues, as urged in the original New Archaeology (e.g. Clarke 1968: 549–551). The social brain estimates roughly the size of "intellectual container" that we need for encapsulating these events. If we see event-type A twice, and 1,000 times we do not, we can feel more comfortable in accepting the evidence at face value, saying, "Well that fits; they were capable of it; but preservation really is as odd a thing as Lyell realised in 1863 (Lyell 1863)". The Social Brain idea may also help us to see what drove the major changes, but this point is less clear. It sees group sizes changing through changes in ecological variables. Increasingly, humans inherited changes caused by their own evolution, and it seems strange that feedback models have largely gone out of fashion. They must surely be indispensable to working out the nature of long-term evolutionary trends. The most striking thing about the evolution of *Homo* is the rapidity of change consistently maintained in continuing trends. We can profit from returning to an interest in their mechanisms.

Material culture has not gone away. It belongs both in the evolutionary dynamics and the detailed picture. In the first, a new comparative picture is emerging as the variations in chimpanzee culture become more apparent, and as the known chimpanzee traits become extended, sometimes dramatically as through the Fongoli spears (Pruetz and Bertolani 2007). Chimpanzee artefacts can be studied in the same way as human ones (e.g. Carvalho et al. 2009; Gowlett 2009b; Lycett et al. 2010), and it is the variation in their culture which will offer some of the best analogies and comparators for human and early human artefact patterning.

The relationship between artefact distribution and cultural boundaries then becomes a central issue: what is proxy for what? Hodder has shown that artefact type and ethnic boundary do not necessarily coincide (Hodder 1977, 1978).

As the interest moves from ethnic units to social networks, further studies are required on the relationship among movement, material value, distance, and area. For the large picture of human evolution, there is more to gain from further studies of social transmission, "culture" and imitation, and many of these will depend directly on artefacts.

Typology is one of the areas which – in the fashion which Arber (1985) describes – has been eclipsed, largely replaced by concepts of social technology (in which signatures extend through time in the making of an artefact, rather than being crystallised in its final form). But the death of typology can be exaggerated – we should go back and take from it what we need, unashamedly, recognising now far more easily that there is no fixed boundary between the static (declarative) and dynamic (procedural and savoir-faire) aspects of making and using tools. The area is also bolstered by the new need for classification and analysis of ape tools. The human ability to handle "many" side by side, whether it is human relationships or artefacts, is another fundamental part of our evolution and helps to justify typology as an agent for studying "multiplicity".

With their large numbers and many characteristics artefacts lend themselves to quantitative study. Some degree of fashion change is seen in the move from univariate and bivariate statistics to multivariate approaches (first made practicable on mainframe computers in the 1970s), and then in the development of new multivariate techniques. Principal components and discriminant analysis remain with us, but cluster analysis seems less used, while the new Morphometrics has gained in popularity. There seems a valid use for all these, again with advantages coming from using pairs of techniques to triangulate on a solution. Hierarchical cluster analysis was used by Daniel Cahen to study Acheulean cleavers as early as 1969 and has been employed recently for the study of matriarchal and patriarchal lineages (Holden and Mace 2003), as well as in genetics; it surely still has more to offer when applied to artefacts.

New is often better, and the Morphometrics has many possibilities. For instance, its techniques allow the analysis of form free of size variation (effects), with particular benefits for archaeology's yearning to explore templates. Such an "ideal" form should not exist in biology, as natural selection is primarily undirected, but in cultural phenomena (and here we hark back to Plato's *Ideals*) the pressures towards norms can create the situation where everyone agrees about the same thing ("it should be just like this"). The implication is that we need to know a great deal more about stereotypes and templates, and how they operate in modern humans, to get even more out of these techniques (see Hodgson 2006 for recent discussion of related issues).

The Detailed View: Slices of Space and Time

The more detailed Archaeology does not offer similar benchmarks, more a continuity of change. The "great archaeologists" set the framework – Francois Bordes' major excavations and his typology dominated the 1950s (Bordes 1972). Leroi-Gourhan's

palaeoethnology and social approach carried greater weight from 1960, when the Pincevent excavations began (Leroi-Gourhan and Brézillon 1972). Clark (1962, 2001) had paved the way at Kalambo Falls, with the concept of area excavations and living surfaces – but no doubt he too had learnt from the earlier great Russian excavations and those of Alfred Rust at the Pinnberg (Rust 1958). Clark Howell grappled with the Somme sequence as well as the problems of Ambrona and Torralba (Howell 1966). Charles McBurney excavated the Haua Fteah and La Cotte de St Brelade (Callow and Cornford 1986; McBurney 1967). This was the excavation landscape. All their works show that quantitative archaeology had begun to filter through ahead of the classic New Archaeology. All in all, there was an accumulation of techniques allowing a broader and better record to be built. Looking forward, the signs are – the inevitability is – that this is what archaeologists will build on in a continuous tradition.

The archaeology of detail is steadily moving towards a wider range of proxies for the past. They still divide essentially into those that are part of the human behaviour and those that are part of the environment. A stone tool is in the first, but its material drawn from the second. A bone with cut marks and hyena tooth marks manages to be part of both.

The frame still divides into site and landscape, the first dominated by denser swarms of artefacts. Then, typology and measurement are still first weapons in the artefact armoury. Microwear study has rarely displaced them and does not look likely to. In artefact study, there is a great separation of form study and function study. The latter is usually studied quite simply as "cutting" or "scraping". We can hope to move towards a more linked-through approach in which the whole artefact is related with biomechanics of the hominin. We can measure things as work that needs to be done. Now that the whole artefact can be captured by 3D scanning it can be studied in many ways as a virtual solid object – as a single specimen, in its biomechanical framework, or as part of a varied horde.

Style studies, as analysed by Sackett, will also have a place. Sackett (1977, 1982) has given a theoretical basis for the relationship between style and function, which has a renewed relevance as we begin to look at variability again in the light of the local variations in chimpanzee culture (Lycett et al. 2009; Whiten et al. 1999). For Sackett, style and function are complementary, everything in the artefact to be accounted for by one or the other. There is great scope for testing such ideas as our data sets and comparative framework improve. Looking across for a moment to the New World (Chap. 14), it is evident that North American scholars have been particularly successful in selecting key aspects of a problem (e.g. style, curation, the *chaîne opératoire*, etc.) and providing detailed thoughtful analysis (e.g. Sackett 1977; Shott 1996; Shott and Sillitoe 2005; Chap. 8).

On the scale of whole site, coordinate plotting of finds continues and has been made far easier by electronic theodolites. Point-pattern studies will thus continue, and often they can be interpreted visually, as when the finds from two adjacent layers are represented with different colours. Such studies are easier and more economic of time than some of the old number crunching. Refitting of artefacts can be shown on the plots, but it still depends on time-intensive searching of collections

and the experienced eye. In the very long term, we might hope for its processes to become automated. The benefits of site-wide studies of patterning and refits are clear – it is simply that the costs are high. Kroll has shown the advantages and pointed out how helpful these analyses can be on the larger sites, such as the Olduvai and East Turkana surfaces (Kroll 1994, 1997).

Landscape studies can sometimes be made on the basis of reconstruction of palaeolandscape, as at Olduvai or East Turkana (Hay 1976; Blumenschine and Peters, 1998; Chap. 7). Very often the site may be in a landscape too changed for direct interpretation. Then we rely even more on the study of raw material transport. Leakey and Hay's work has been followed and amplified in Europe by Geneste (1991) and acute accent: Féblot-Augustins (1999). Linking site and landscape, Schick and Toth emphasise artefact imports and exports that tell us of dynamics (Schick 1987; Schick and Toth 1993; Toth 1987; Toth and Schick 2004). Gamble (1999) has told us of networks and social landscapes, Aureli et al. (2008) of the fission and fusion which underlie the patterns of movement. There is vast scope to put these together. Essentially population groups hold ground. The further an individual travels from that ground, in linear movement, the more there needs to be negotiation – a social passport. Artefacts offer just a dim shadow of these movements, emphasising a need for new modelling of potential frameworks, some of it at least by agent-based techniques (e.g. Sellers et al. 2007, in the case of baboon foraging). Traditionally much of the interpretation has been made in terms of exchange and alliance – but there may of course be other explanations. Hodder (1977, 1978) explained the difficulty of distinguishing between different "fall off" distributions, as their feature in common tends to be very poor sampling of the fringes (i.e. the flange of the bell in a bell curve).

We do know for sure that larger scales of group have emerged in human evolution. They have acknowledged importance as "superbands" and "dialect tribes" (Tindale 1940; Wobst 1974). How can we see them? An issue emerging via evolutionary psychology is that such groups are scaled, rising with a common factor of ca. 3–4 (Zhou et al. 2005). In chimpanzees, the community is the largest visible entity. Modern humans always reckon part of their identity from groups measured in hundreds or thousands. Archaeological evidence for such larger groups may turn out to be indirect (i.e. not expressed as larger sites, *pace* those archaeologists who have expected to see these in the "human revolution" – those who write in these terms are often unaware of the sheer scale of early African sites). A mixture of empirical and modelling approaches may be necessary to gain better understanding of this crucial group scaling (Clarke 1968; Isaac 1972; Steele 1994; Grove 2009; Zhou et al. 2005).

Alongside our own artefact studies, the area more traditionally known to the Physical Sciences and Chemistry as "Analysis" now forms a major area of "archaeological science", but not in a very systematic way for the Palaeolithic. In its application, we might expect to find by now a sort of "rule book" applicable to every situation. In practice, the needs vary enormously according to situation. On one site chemical analysis and sourcing of rocks may be necessary; on another the key facts may be visible to the naked eye. But these techniques are often the means of identification of rocks, tuffs, and raw materials as already mentioned. Other problems

are tackled successfully through studies of stable isotopes (cf. Backwell and d'Errico 2005). Although these include especially studies of diet from bone, other techniques can be brought into play such as analysis of habitat association (de Ruiter et al. 2008). Occasionally phytoliths on lithic artefacts have given clues of function (Domínguez-Rodrigo et al. 2001), and old staples such as pollen analysis sometimes bear fruit in environmental reconstruction, so we may expect a constant reworking and refinements of such techniques, applied singly or in conjunction.

While studies are still largely "site-centred" a generation after "off-site archaeology" was first mooted (Foley 1977), the pictures that emerge seem much more complete and relate more to inputs and outputs.

Debit and Credit

Mary Leakey used to talk of putting finds of doubtful status into the "suspense account". Here she placed the first derived artefacts from Hadar, found in gravels (Corvinus and Roche 1976). In a similar valuation, we might talk of debit and credit in newer approaches.

Now we can return for a moment to Isaac's *Whither archaeology?* (1971), to put his ideas in the scales. First, Isaac defended modernization in Archaeology – it was necessary, and still is. He also noted, above all, the need for a discipline to maintain its factual basis, and again that still helps us. But then he noted especially Archaeology's new sense of building itself as a separate discipline – here I believe danger began. Over the years, Archaeology as a whole, through its obsessions with theory, and the heavy load of detail, has addressed its own community rather than reaching out, and so has lost impact. It must learn to regain it.

Then, we have a battery of powerful and sometimes new techniques, but Archaeology and analysis are not necessarily improved with the passage of time. Practitioners do not necessarily grasp better perspectives. In Britain at least, those coming into the discipline have less and less scientific and mathematical background, and they sometimes fall into traps that they would have seen a generation ago. Although the New Archaeology sets an excellent direction on the topic, often we do not handle sampling issues well. We do not look out to disciplines with comparable problems, for example, astronomy. Astronomy has all our uncertainties – sometimes orders of magnitude more – and is more efficient and fair-minded in selecting its working hypotheses. Archaeologists are discomfited by having a 500,000-year range of doubt in the origins of this or that technique or practice. They tend to respond by taking a conservative view, thinking that "late is safe", even though this often means choosing to be wrong. Astronomers will simply mark out a range of uncertainty and work on reducing it. Good science takes out value judgements.

These issues are becoming more important, because Archaeology has felt that it had first right to control interpretation of the past, but it is having to admit the claims of other disciplines to paint in the record. In many ways, the development is

good, because it is leading to a very gradual erosion of "WYSWTW", and a better appreciation of past worlds that are bigger than our own materially restricted one.

Last, on the debit side, we seem not very transparent about the law of diminishing returns. We still fill in time doing *something* to an archaeological assemblage, rather than nothing – a great deal of measuring goes on that will not have a measurable return. On the other hand, to be positive, our position is somewhat like that in police work, where there can be a decision to concentrate on serious crime, and huge investment in a murder committed years ago may have unexpected payoffs. My strictures should not have too serious a ring, because part of what we need to do is to put the fun back into Archaeology.

Where Is this Going Now? Concluding Thoughts

So what is our task in the future? This will be shaped by many archaeologists, not one person's opinion. It seems inevitable that there will be much more of the same – the construction of detailed pasts from local artefact records, and the search for grander scale evolutionary dynamics. The second depends on the first – the basis of sound data.

Helping with this development is a gradual extension of involvement with material culture, beyond the old preoccupation with lithics, to other materials (e.g. Chap. 2), and even beyond human tools per se (e.g. Chap. 5).

In all this is a gradual engagement with the issues of other disciplines. We are not alone in noting the blindspots in the coming together. Often they are even worse than us in neglecting relevant literature. Note how Bickerton (2003) calls for a broader cross-disciplinary appreciation in early language studies: it should not, he urges, be beyond us to look around and master the basics of several disciplines – and we need to do so, because our explanations have to be valid in all of them.

Such "whole world" considerations (perhaps best not use the word "holistic" which now smacks of alternative therapies) – turning to language itself – can help us to a better understanding of how language begins to operate on social tradition. Recent definitions of culture (e.g., Boesch 2003) include "shared understanding" – but as anthropologists we can also ask how do we know that the understanding is shared? What does sharing mean? As "jointly partaking" it means far less than "exchanging insights", and archaeological data might often show the first, only hinting at the second. As archaeologists are well used to analysing data and ideas in a very painstaking way, they should be able to investigate these issues as well as any discipline – we can only give detail to the rise of intentionality if we have our own good insights into its nature.

We also need a better understanding of what trends entail. How surprisingly little is written about the *nature* of evolutionary trends (with Clarke 1968 and Janis and Damuth 1990 as rare exceptions). In the strictest sense, they have no meaning because evolution has no purposeful direction. At each moment, different selection pressures would lead to a different direction of response. But the trends do occur,

and they do have significance in human interpretation – we are interested in how things have happened over long periods, and any prolonged response helps us to discern factors which have operated consistently through time.

This interpretation of trends – the study of rates of change – is of course crucial in the discipline. It goes back to our measured quantities, such as stone artefacts and dates, and highlights the importance of mathematical models (cf. Chaps. 5, 8, 12). Its principle is also what allows us to hazard a guess at the future – from a plot of past changes. To summarise, here are some few things that we might aim for.

To seize again the impact that is due to our discipline – to emphasise the role of Archaeology as the main custodian of the past record.

To operate in our discipline with more strategic purpose, by grand design (as do astronomers and even primatologists), setting out goals for future study.

To articulate better and more explicitly with neighbouring disciplines, such as evolutionary anthropology, primatology, genetics, and evolutionary psychology.

To give strong support to varying scales of projects: the smaller are often highly focused, and give very good returns, the larger offer a scale that provides answers otherwise completely unavailable.

In detailed analysis, we could aim to operate with a more readily available manual of rigorous approaches, looking to earlier work for the best in it, rather than discarding much of our own record simply because it was reported more than a few years ago. There is the real challenge – a mature archaeology cannot operate with a time bar. But if there is any risk of analytical impoverishment, this volume shows the contrary.

And finally, should we indeed be looking for a new -ism? That might be available in the "social brain" or in a new generation of cultural studies inspired by developments in the primate world. I think it will come from somewhere else. It will probably be introduced by younger archaeologists. It will have good and bad points, but it will lever our past into the future.

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References

Aiello, L.C. and Dunbar, R.I.M., 1993. Neocortex size, group size, and the evolution of language. *Current Anthropology* 34: 184–193.

Aiello, L.C. and Key, C., 2002. Energetic consequences of being a *Homo erectus* female. *American Journal of Human Biology* 14: 551–565.

Aiello, L.C. and Wheeler, P., 1995. The expensive tissue hypothesis: the brain and the digestive system in human and primate evolution. *Current Anthropology* 36: 199–221.

Ambrose, S.H., 1998. Late Pleistocene human population bottlenecks, volcanic winter, and differentiation of modern humans. *Journal of Human Evolution* 34: 623–651.

Arber, A., 1985. *Mind and the Eye*. Cambridge University Press, Cambridge.

Aureli, F., Schaffner, C., Boesch, C., Bearder, S., Call, J., Chapman, A., Connor, R., Di Fiore, A., Dunbar, R.I.M., Henzi, S.P., Holekamp, K., Korstjens, A.H., Layton, R., Lee, P., Lehmann, J., Manson, J.H., Ramos-Fernandez, G., Strier, K.B., and van Schaik, C.P., 2008. Fission–fusion dynamics: new research frameworks. *Current Anthropology* 49: 627–654.

Backwell, L. and d'Errico, F., 2005. The origin of bone tool technology and the identification of early hominid cultural traditions. In *From Tools to Symbols: from Early Hominids to Modern Humans*, edited by F. d'Errico and L. Backwell, pp. 238–275. Witwatersrand University Press, Johannesburg.

Barham, L., 2002. Systematic pigment use in the Middle Pleistocene of South Central Africa. *Current Anthropology* 43: 181–190.

Bickerton, D., 2003. Symbol and structure: a comprehensive framework for language evolution. In *Language Evolution* edited by M. Christiansen and S. Kirby, pp. 77–93. Oxford University Press, Oxford.

Binford, L.R., 1983. *In Pursuit of the Past*. Academic, London.

Bintliff, J., 1991. *The Annales School and Archaeology*. Leicester University Press, Leicester.

Bintliff, J., 2003. Time, structure and agency: the annales, emergent complexity and archaeology. In *A Companion to Archaeology*, edited by J. Bintliff, pp. 174–194. Blackwell, Oxford.

Blumenschine, R.J. and Peters, C.R., 1998. Archaeological predictions for hominid land use in the paleo-Olduvai Basin, Tanzania, during lowermost Bed II times. *Journal of Human Evolution* 34: 565–607.

Boesch, C., 2003. Is culture a golden barrier between human and chimpanzee? *Evolutionary Anthropology* 12: 82–91.

Bordes, F.H., 1972. *A Tale of Two Caves*. Harper and Row, New York.

Boucher de Perthes, J., 1864. *Antiquités celtiques et antediluviennes: mémoirs sur l'industrie primitive et les arts à leur origin (part 3)*. Treuttel et Wurtz, Paris.

Braüdel, F., 1972. *The Mediterranean and the Mediterranean World in the age of Philip II*. London: Fontana/Collins (2 volumes).

Byrne, R.W. and Whiten, A. (eds), 1988. *Machiavellian Intelligence: Social Expertise and the Evolution of Intellect in Monkeys*. Oxford University Press, Oxford.

Callow, P. and Cornford, P.M., 1986. *La Cotte de St. Brelade, 1961–1978: Excavations by C.B.M. McBurney*. Geobooks, Norwich.

Carvalho, S., Biro, D., McGrew, W.C., and Matsuzawa, T., 2009. Tool-composite reuse in wild chimpanzees (*Pan troglodytes*): archaeologically invisible steps in the technological evolution of early hominins? *Animal Cognition* 12: 103–114.

Clark, J.D. 1962. The Kalambo Falls prehistoric site: an interim report. In *Actes du IVe Congres Pan-africain de Prehistoire et de l'Etude du Quaternaire*, edited by G. Mortelmans and J. Nenquin, pp. 195–201. Royale de l1Afrque centrale, Annales, Serie in 8eme, Sciences humainesù 40, Section III.

Clark, J.D. (ed.), 2001. *Kalambo Falls, Vol 3*. Cambridge University Press, Cambridge.

Clark, J.D., Cole, G.H., Isaac, G.Ll., and Kleindienst, M.R., 1966. Precision, and definition in African archaeology. *South African Archaeological Bulletin* 21: 114–121.

Clarke, D.L., 1968. *Analytical Archaeology*. Methuen, London.

Corvinus, G. and Roche, H., 1976. La préhistoire dans la région de Hadar (bassin de l'Awash, Afar, Ethiopie): premiers résultats. *L'Anthropologie* 80: 315–324.

Domínguez-Rodrigo, M., Serrallonga, J., Alcalá, L., and Luque, L., 2001. Woodworking activities by early humans: a plant residue analysis on Acheulian stone tools from Peninj (Tanzania). *Journal of Human Evolution* 40: 289–299.

Dunbar, R.I.M., 1998. The social brain hypothesis. *Evolutionary Anthropology* 6: 178–190.

Dunbar, R.I.M., 2003. Evolution of the social brain. *Science* 302: 1160–1161.

Dunbar, R., Gamble, C., and Gowlett, J. (eds), 2010. *Social Brain, Distributed Mind*. The British Academy, London.

Féblot-Augustins, J., 1999. Raw material transport patterns and settlement systems in the European Lower and Middle Palaeolithic: continuity, change and variability. In *The Middle Palaeolithic Occupation of Europe*, edited by W. Roebroeks and C. Gamble, pp. 193–214. European Science Foundation and University of Leiden, Leiden.

Foley, R., 1977. Space and energy: a method for analysing habitat values and utilization in relation to archaeological sites. In *Spatial Archaeology*, edited by D.L. Clarke, pp. 163–187. Academic, London.

Gamble, C.S., 1999. *The Palaeolithic Settlement of Europe*. Cambridge University Press, Cambridge.

Gamble, C., 2007. *Origins and revolutions: human identity in earliest prehistory*. Cambridge University Press, Cambridge.

Gamble, C. and Kruszynski, R., 2009. John Evans, Joseph Prestwich and the stone that shattered the time barrier. *Antiquity* 83: 461–475.

Gamble, C.S. and Porr, M. (eds), 2005. *The Hominid Individual in Context: Archaeological Investigations of Lower and Middle Palaeolithic Landscapes, Locales and Artefacts*. Routledge, London.

Gargett, R.H., 1989. Grave shortcomings: the evidence for Neandertal burial. *Current Anthropology* 30: 157–190.

Gargett, R.H., 1999. Middle Palaeolithic burial is not a dead issue: the view from Qafzeh, Saint-Césaire, Kebara, Amud, and Dederiyeh. *Journal of Human Evolution* 37: 27–90.

Geneste, J., 1991. L'approvisionnement en matières premières dans les systèmes de production lithique: la dimension spatiale de la technologie. In *Tecnología y Cadenas Operativas Líticas*, edited by R. Mora, X. Terradas, A. Parapl, and C. Plana. *Treballs d'Arquelogia* 1: 1–35.

Gowlett, J.A.J., 1997. Why the muddle in the middle matters: the language of comparative and direct in human evolution. In *Rediscovering Darwin: Evolutionary theory in archaeological explanation*, edited by C.M. Barton and G.A. Clark, pp. 49–65. University of Arizona Press, Arizona/AAAS.

Gowlett, J.A.J., 2009. Boucher de Perthes: pioneer of Palaeolithic prehistory. In *Great Prehistorians: 150 Years of Palaeolithic Research, 1859–2009*, edited by R. Hosfield, F. Wenban-Smith and M. Pope, pp. 13–24. Lithic Studies Society, London. (Special Volume 30 of *Lithics*, The Journal of the Lithic Studies Society).

Gowlett, J.A.J., 2009a. The longest transition or multiple revolutions? Curves and steps in the record of human origins. In *Sourcebook of Paleolithic Transitions: Methods, Theories and Interpretations*, edited by M. Camps and P.R. Chauhan, pp. 65–78. Springer, New York.

Gowlett, J.A.J., 2009b. Artefacts of apes, humans and others: towards comparative assessment. *Journal of Human Evolution* 57: 401–410.

Green, R.E., Krause, J., Ptak, S.E., Briggs, A.W., Ronan, M.T., Simons, J.F., Lei Du, Egholm, M., Rothberg, J.M., Paunovic, M., and Paabo, S., 2006. Analysis of one million base pairs of Neanderthal DNA. *Nature* 444: 330–336.

Grove, M., 2009. The archaeology of group size. In *Social Brain, Distributed Mind*, edited by R. Dunbar, C. Gamble and J. Gowlett, pp. 395–415. The British Academy, London.

Hay, R.L., 1976. *Geology of the Olduvai Gorge*. University of California Press, California.

Hodder, I., 1977. The distribution of material culture items in the Baringo District, Western Kenya. *Man NS* 12: 239–269.

Hodder, I., 1978. Some effects of distance on patterns of human interaction. In *The Spatial Organization of Culture*, edited by I. Hodder, pp. 155–178. Duckworth, London.

Hodgson, D., 2006. Understanding the origins of Palaeoart: the neurovisual resonance theory and brain functioning. *Palaeoanthropology* 2006: 54–67.

Holden, C.J. and Mace, R., 2003. Spread of cattle led to the loss of matrilineal descent in Africa: a coevolutionary analysis. *Proceedings of the Royal Society of London B* 270: 2425–2433.

Howell, F.C., 1966. Observations on the earlier phases of the European Lower Palaeolithic. In *Recent Studies in Palaeoanthropology*, edited by J.D. Clark and F.C. Howell, pp. 88–201. American Anthropological Association Special Publication 68, Washington DC.

Isaac, G.Ll., 1969. Studies of early culture in East Africa. *World Archaeology* 1: 1–28.
Isaac, G.Ll., 1971. Whither archaeology? *Antiquity* 45: 123–129.
Isaac, G.Ll., 1972. Chronology and the tempo of cultural change during the Pleistocene. In *The Calibration of Hominoid Evolution*, edited by W.W. Bishop and J.A. Miller, pp. 381–430. Scottish Academic, Edinburgh.
Janis, C.M. and Damuth, J., 1990. Mammals. In *Evolutionary Trends* edited by K.J. McNamara, pp. 301–345. Belhaven, London.
Krause, J., Lalueza-Fox, C., Orlando, L., Enard, W., Green,R.E., Burbano, H.A., Hublin, J.J., Hänni, C., Fortea, J., de la Rasilla, M., Bertranpetit, J., Rosas, A., and Pääbo, S., 2007. The derived FOXP2 variant of modern humans was shared with Neandertals. *Current Biology* 17: 1–5.
Krings M., Stone A., Schmitz R.W., Krainitzki H., Stoneking M., and Paabo S., 1997. Neandertal DNA sequences and the origin of modern humans. *Cell* 90: 19–30.
Kroll, E.M., 1994. Behavioural implications of Plio-Pleistocene archaeological site structure. *Journal of Human Evolution* 27: 107–138.
Kroll, E.M., 1997. Lithic and faunal distributions at eight archaeological excavations. In *Koobi Fora Research Project Volume 3: Plio-Pleistocene Archaeology*, edited by G.Ll. Isaac and B. Isaac, pp. 459–543. Clarendon, Oxford.
Leakey, L.S.B., 1959. A new fossil skull from Olduvai. *Nature* 184: 491–493.
Leakey, M.D., 1978. Olduvai Gorge 1911–1975: a history of the investigations. In *Geological Background to Fossil Man*, edited by W.W. Bishop, pp. 151–156. Scottish Academic, Edinburgh.
Leroi-Gourhan, A. and Brézillon, M., 1972. *Fouilles de Pincevent. Essai d'Analyse Ethnographique d'un habitat Magdalénien (La Section 36)*. VII Supplement to *Gallia Préhistoire* Editions. CNRS, Paris.
Lycett, S.J., Collard, M., and McGrew, W.C., 2009. Cladistic analyses of behavioral variation in wild *Pan troglodytes*: exploring the chimpanzee culture hypothesis. *Journal of Human Evolution* 57: 337–349.
Lycett, S.J., Collard, M. and McGrew, W.C., 2010. Are behavioral differences among wild chimpanzee communities genetic or cultural? An assessment using tool-use data and phylogenetic methods. *American Journal of Physical Anthropology* 142(3): 461–467.
Lyell, C., 1863. *The Geological Evidences of the Antiquity of Man*. John Murray, London.
McBrearty, S. and Brooks, A.S., 2000. The revolution that wasn't: a new interpretation of the origin of modern human behavior. *Journal of Human Evolution* 39: 453–563.
McBurney, C.B.M., 1967. *The Haua Fteah (Cyrenaica) and the Stone Age of the South-East Mediterranean*. Cambridge University Press, Cambridge.
Pruetz, J.D. and Bertolani, P., 2007. Savanna chimpanzees, *Pan troglodytes verus*, hunt with tools. *Current Biology* 17: 1–6.
de Ruiter D.J., Sponheimer, M., and Lee-Thorp, J.A., 2008. Indications of habitat association of Australopithecus robustus in the Bloubank Valley, South Africa. *Journal of Human Evolution* 55: 1015–1030.
Rust, A., 1958. *Die Funde vom Pinnberg*. Karl Wachholtz Verlag, Neumunster.
Sackett, J.R., 1977. The meaning of style in archaeology: a general model. *American Antiquity* 42: 369–380.
Sackett, J.R., 1982. Approaches to style in lithic archaeology. *Journal of Anthropological Archaeology* 1: 59–122.
Schick, K.D. and Toth, N., 1993. *Making Silent Stones Speak: Human Evolution and the Dawn of Technology*. Simon and Schuster, New York.
Schick, K.D., 1987. Modelling the formation of stone artifact concentrations. *Journal of Human Evolution* 16: 789–807.
Sellers, W.I., Hill, R.A., and Logan, B.S., 2007. An agent-based model of group decision making in baboons. *Philosophical Transactions of the Royal Society B* 362: 1699–1710.
Shott, M.J., 1996. An exegesis of the curation concept. *Journal of Anthropological Research* 52: 259–280.

Shott, M.J. and Sillitoe, P., 2005. Use life and curation in New Guinea experimental used flakes. *Journal of Archaeological Science* 32: 653–663.

Steele, J., 1994. Communication networks and dispersal patterns in human evolution: a simple simulation model. *World Archaeology* 26: 126–143.

Stewart, I., 1995. *Nature's Numbers: Discovering Order and Pattern in the Universe*. Weidenfeld and Nicolson, London.

Thomsen, C.J., 1836. *Ledetraad til nordisk Oldkyndighed* (*A Guide to Northern Antiquities*). Copenhagen.

Tindale, N.B., 1940. Results of the Harvard–Adelaide Universities anthropological expedition, 1938–1939: distribution of Australian aboriginal tribes: a field survey. *Transactions of the Royal Society of South Australia* 64: 140–231.

Toth, N., 1987. Behavioral inferences from early stone age assemblages: an experimental model. *Journal of Human Evolution* 16: 763–787.

Toth, N. and Schick, K. (eds), 2004. *The Oldowan: Case Studies into the Earliest Stone Age*. Stone Age Institute Press, Bloomington, Indiana.

Trinkaus, E. and Shipman, P., 1993. *The Neandertals: Changing the Image of Mankind*. Jonathan Cape, New York.

Wang, W.J. and Crompton, R.H., 2004. The role of load-carrying in the evolution of modern body proportions. *Journal of Anatomy* 204: 417–430.

Whiten, A., Goodall, J., McGrew, W.C., Nishida, T., Reynolds, V., Sugiyama, Y., Tutin, C.E.G., Wrangham, R.W., and Boesch, C., 1999. Cultures in chimpanzees. *Nature* 399: 682–685.

Whiten, A., Schick, K., and Toth, N., 2009. The evolution and cultural transmission of percussive technology: integrating evidence from palaeoanthropology and primatology. *Journal of Human Evolution* 57: 420–435.

Wobst, H.M., 1974. Boundary conditions for Palaeolithic social systems: a simulation approach. *American Antiquity* 39: 147–178.

Zhou, W.-X., Sornette, D., Hill, R.A., and Dunbar, R.I.M., 2005. Discrete hierarchical organization of social group sizes. *Proceedings of the Royal Society of London B* 272: 439–444.

Chapter 14
The Future of Paleolithic Studies: A View from the New World

Michael J. O'Brien

Abstract Paleolithic studies have a long tradition in European and American archaeology, beginning in serious fashion with the work of John Lubbock in Britain and later with that of William Henry Holmes in the United States. Research questions that have been asked with respect to the Paleolithic period have changed dramatically over the decades, but the interest in stone tools as major sources of information on prehistoric peoples has not. In the New World, the last decade has witnessed a shift in research emphasis back to questions of culture history, but the methods and techniques now being brought to bear on the questions are entirely modern in how they address issues of cultural relatedness. Without an ability to distinguish between cases of technological convergence and cases of homologous similarity, we can never hope to untangle prehistory. The methods and techniques now being used are geared specifically for that purpose. Most important, they yield testable results as opposed to impressions. As a result, we now have unparalleled views into Paleolithic life in the New World.

Introduction

I appreciate the invitation to contribute a chapter to this volume. I state at the outset that I am not a Paleolithic specialist, usually finding myself on the sidelines when the subject turns to the finer points of stone-tool manufacture or how to recognize various traces of use-wear. I have, however, developed some degree of competency with respect to ways in which stone tools can be used to answer interesting archaeological questions, and it is solely from that perspective that I write this essay. I subtitle the piece "*A* View" because that's what it is – not a long-range perspective of where Paleolithic studies might be 20 years from now but rather a narrow view of what I see as some interesting research questions and the promising avenues that are being followed to answer them.

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I have no adequate means of calculating the number of publications focusing primarily or exclusively on the Paleolithic that appear annually, but it is substantial. The sheer number of studies ensures that competing views are always in the mix – a pluralism that presents an extraordinarily diverse smorgasbord from which future studies can sample. Certainly, the chapters included here attest to that pluralism. I limit my discussion, however, to what might broadly be defined as culture history, but I come at it from the standpoint of evolution. In that respect, I echo Kuhn's (2004:561) remark that "evolutionary concepts and models provide some of the best tools for learning about the kinds of long-term processes that engage my interest."

I sometimes wonder what prehistorians working a 100 years ago would think of the myriad directions in which archaeology has headed. For example, what would William Henry Holmes think of modern Paleolithic studies? Certainly Holmes, from his vantage point in the Bureau of American Ethnology, witnessed the prominent role that stone artifacts played in understanding the Paleolithic of both Europe and North America, especially with respect to the antiquity of human occupation of the latter. More important here was the role that Holmes played. In several clear, not to mention clever, expositions of the problems one can face in putting all one's eggs in an analogical basket, Holmes brilliantly succeeded in demonstrating that supposed widespread evidence of glacial-age humans in North America was, in fact, no evidence at all.

As received wisdom had it (e.g., Abbott 1881), if certain chipped-stone artifacts from North America were identical in form to those recovered from undisputed early (glacial-age) European Paleolithic contexts, then North America had experienced its own early Paleolithic stage. One characteristic of many of the chipped-stone pieces recovered from North American contexts was their crude appearance – cruder certainly than the well-made projectile points and other shaped tools familiar to North American prehistorians. Given the then-current views on cultural evolution and the ladderlike nature of unilinear evolutionary schemes made popular by Lubbock (1865) and others, it was difficult *not* to make the assumption that technologically "inferior" tools (or, more precisely, what were assumed to be tools) were left by earlier people – a position that appeared to be strengthened by reports of similar inferior pieces being found in glacial-age gravel deposits across the midwestern and eastern United States. Prehistorians reasoned that if the gravel beds dated to the glacial period, and the beds contained tools, then the obvious conclusion was that humans had inhabited North America during the so-called "ice age."

The faulty logic behind this argument was not lost on Holmes, who began as early as 1890 with a series of articles aimed at discrediting the great antiquity of humans in the New World (e.g., Holmes 1893). These led to his excavations in Piney Branch and related stone quarries in and around Washington, D.C., and finally to his article "Stone Implements of the Potomac – Chesapeake Tidewater Province" (Holmes 1897). In it, Holmes conclusively demonstrated that what were considered to be early "tools" were nothing more than quarry blanks and rejects. Several decades later, a small projectile point from northeastern New Mexico (Figgins 1927) would demonstrate that indeed humans *had* been in North America much earlier than Holmes expected, but that's not important here. What *is* important is the take-home

message that came from Holmes's work: Don't confuse analogous similarity with homologous similarity. Homology implies *relatedness* through some transmission process, whereas analogy implies convergence on a common solution to a problem without transmission. The issue would appear to be particularly consequential with respect to Paleolithic studies, where, on the one hand, "patterns in technology have been used to reconstruct population histories… . [while] on the other hand stone tools can be and have been interpreted as adaptive markers, often with little or no phylogenetic signal, because they are endlessly thrown up convergently by the demands of the environment and social organization, which thus reflect variability in behavioral response" (Foley and Lahr 2003:110). In other words, there are only so many ways to make stone tools, and unrelated toolmakers must have found common solutions to environmental "problems" countless times the world over. How does one know when two things are similar because they are related as opposed to possibly being related because they are similar?

I examine the issue of analogous versus homologous similarity in more detail below, using that discussion as a lead-in to a broad issue that underlies many of the chapters here, cultural transmission. In my opinion, there is no "hotter" topic in archaeology and one that transcends where in the world one works or where one was trained. In one respect, it is rather ironic to state that cultural transmission is currently a hot topic, given the centrality of transmission, in one guise or another, in archaeology from the beginning (Lyman 2008), but in contrast to many early studies, those of today exhibit a commitment to theory in the scientific sense of the word, and they are designed specifically to examine theoretical implications stemming from formal models (Shennan 2000). But all of those models, whether stated explicitly or not, are built on homology (i.e., a notion of shared ancestry). By definition, how could it be otherwise? Regardless of whether transmission occurs vertically – from parent to child – or horizontally – from peer to peer – it is homologous. As I discuss later, models of social learning, which examine, for example, the kinds of biases that affect the outcomes of transmission, are undeniably useful tools in the social sciences, but they cannot tell us whether traits specific are homologous or analogous to other artifacts. We have to make that distinction on other grounds.

Separating Analogy from Homology

In the late 1960s, Binford (1968:8) identified the lack of a method to distinguish between homologous and analogous cultural similarities as "a basic, unsolved problem" in archaeology. Binford's analytical interest was on function, or analogous similarity, rather than on homologous similarity, but regardless, he needed a means of distinguishing between the two, as was made evident in his debates with Bordes over the nature of Mousterian tool kits from the Dordogne (e.g., Binford 1973). Binford was not the first archaeologist to point out the differences between analogs and homologs in terms that would be familiar to any biologist, nor was he

the first to point out the difficulties involved in separating the two empirically. This is what Kroeber (1931:152–153) had to say on the subject:

> There are cases in which it is not a simple matter to decide whether the totality of traits points to a true relationship or to secondary convergence. … Yet few biologists would doubt that sufficiently intensive analysis of structure will ultimately solve such problems of descent. … There seems no reason why on the whole the same cautious optimism should not prevail in the field of culture; why homologies should not be positively distinguishable from analogies when analysis of the whole of the phenomena in question has become truly intensive. That such analysis has often been lacking but judgments have nevertheless been rendered, does not invalidate the positive reliability of the method.

Although Kroeber was clear that there are two forms of similarity – one homologous and the other analogous – he was less than clear as to how the two can actually be distinguished. He suggested that identifying "similarities [that] are specific and structural and not merely superficial … has long been the accepted method in evolutionary and systematic biology" (Kroeber 1931:151), but he offered no advice on how to separate what is "specific and structural" from what is "merely superficial" beyond undertaking a "sufficiently intensive analysis of structure." Exactly what Kroeber meant by that was unstated.

To culture historians such as Kroeber, formal similarities between cultural phenomena signified some kind of ethnic relation – a predictable result of using ethnologically documented mechanisms such as diffusion and enculturation to account for typological similarities in the archaeological record (Lyman et al. 1997). No one realized it, but this was tautological and put the cart before the horse. Thus, Willey's (1953:363) statement that "typological similarity is an indicator of cultural relatedness (and this is surely axiomatic to archaeology), [and thus] such relatedness carries with it implications of a common or similar history" caused little or no concern within the discipline. It might have caused considerable concern because the axiom falls prey to a caution raised by paleontologist George Gaylord Simpson (1961), using monozygotic twins as an example: They are twins not because they are similar; rather, they are similar because they are twins and thus share a common history.

Someone who was writing at the same time when Binford was pointing out the "unsolved problem" in archaeology also understood the need to keep analogous and homologous similarity separate. That someone was David Clarke. As Lee Lyman and I were writing *Applying Evolutionary Archaeology: A Systematic Approach* (O'Brien and Lyman 2000), we reread Clarke's (1968) *Analytical Archaeology* and were again impressed by the insights that he brought to a wide range of topics.[1] One insight was manifest in how he approached the problems of measuring similarity and detecting *heritable continuity* (O'Brien and Lyman 2000) – the notion that B is related to A (a homology) as opposed to simply following A in a historical sequence. Clarke well understood the importance of transmission to maintaining heritable continuity, and he anticipated the arguments of evolutionary archaeology two decades later when he remarked that "it is the artefact maker who feeds back into the phenotypic constitution of the next generation of artefacts the modified characteristics of the preceding population of artefacts, and it is in this way that the artefact population has continuity in its trajectory and yet is continuously shifting its attribute format and dispersion"

(Clarke 1968:181). As Lyman and I pointed out, Clarke explicitly identified Gould's (1991) phenetic–cladistic distinction when he defined *phenetic relationship* as "relationship based on overall affinity assessed on the basis of the attributes of the entities concerned; without any necessary implication of relationship by ancestry" and *phylogenetic relationship* as "relationship by ancestry; transform types from single multilinear time-trajectory, or tradition" (Clarke 1968:229).

Here, the term *tradition* had its basic archaeological meaning – an evolutionary lineage of some, usually unstated, kind – and the term *trajectory* was basically a synonym for tradition, with explicit recognition that it could vary in scale; a trajectory is "the successive sequence of states of an attribute, entity, or vector generated by successive transformations" (Clarke 1968:82). The term *transform type* meant "the relationship existing between successive and collateral type-states from a single multistate artifact-type trajectory" (Clarke 1968:229). In short, a transform was a transition or change, and a transform type was any state of phenomena at a particular time within a lineage. Thus, transform types "are descent related and are really successive or multilineage type-states" (Clarke 1968:211).

Clarke (1968:148) was keenly aware of the reticulate nature of cultural evolution – an issue I discuss later:

> The taxonomic assessment of affinity between entities will suggest the limited number of possible transformation trajectories which might link the network of particular entities in passing time. Great care must then be taken to avoid the danger of interpreting affinity relationships simply as descent relationships – a condition further complicated by the peculiar nature of branch convergence and fusion found in cultural phylogeny.[2] This problem can only be controlled by providing an adequate chronological frame and by postulating multiple alternative hypotheses of development to link the established degree of affinity between sets of entities under investigation.

The model of change that Clarke developed was couched in terms of systems theory, which was popular at the time, but it was remarkably similar to a metaphor for culture change that the mid-twentieth-century American cultural historian James Ford had used. Whereas Ford (e.g., 1952) used the metaphor of a flowing, braided stream, Clarke used the metaphor of a braided cable:

> [W]e have a static model expressing the structure of an artefact-type population as a nucleated constellation of attributes arranged in clustered complexes and secondary nuclei in terms of the attribute intercorrelation in n-dimensional space. We now wish to develop some model of the kinematic trace or time-trajectory "behaviour" of successive generations or phase populations of these artifacts – the phenetic output of one phase being the input of the succeeding phase … . The arbitrarily expressed system trajectory of the developing artefact-type population may be arbitrarily expressed as a single overall integration of such subsystems and lineages within a single multilinear and mosaic development. The archaeological record provides sporadic and successive sections of strands within this continuous cable of development and it is the relative ordering of these sample phase sections in relation to the orientation of the tradition cable that most exercises the archaeologist's researches. (Clarke 1968:210)

Clarke (1968:211) then turned to the problem of concern here:

> One of the fundamental problems that the archaeologist repeatedly encounters is the assessment of whether a set of archaeological entities are connected by a direct cultural

> relationship linking their generators or whether any affinity between the set is based on more general grounds. This problem usually takes the form of an estimation of the degree of affinity or similarity between the entities and then an argument as to whether these may represent a genetic and phyletic lineage or merely a phenetic and non-descent connected affinity.

Clarke then basically reiterated the criteria long used by culture historians for assessing affinity: The more similar two phenomena are, the more characteristics they share, and the more correlations between "idiosyncratic attributes"

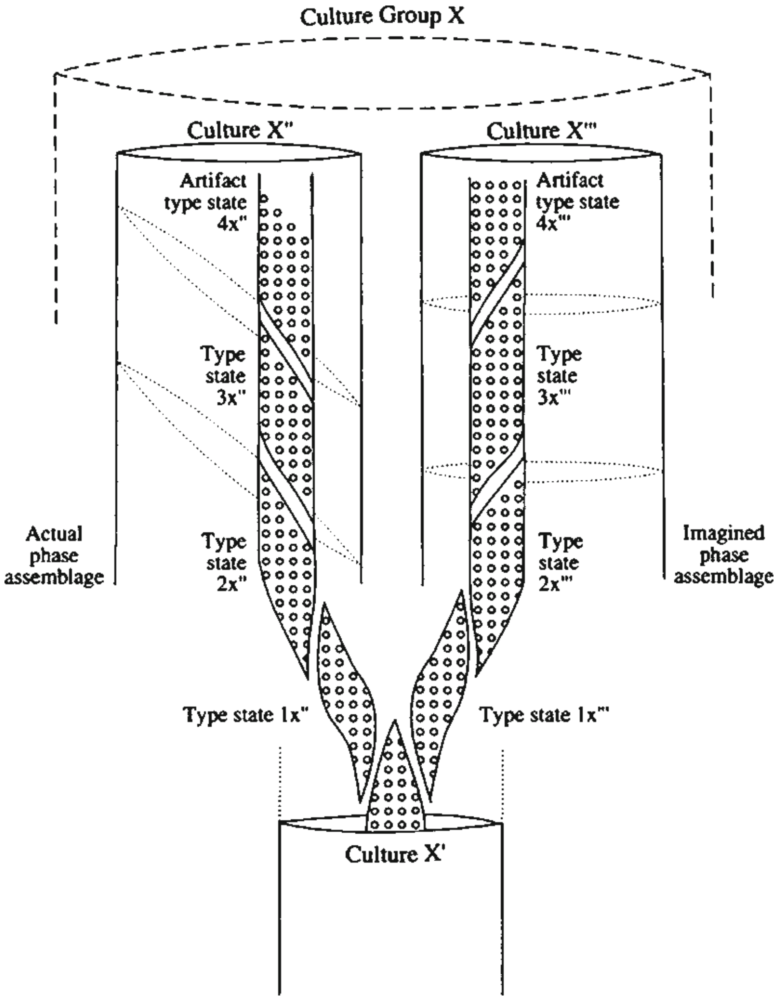

Fig. 14.1 David L. Clarke's (1968) model of culture change. Time may be passing from bottom to top or from top to bottom. Each branch is a lineage, and a "type state" is a cultural unit within a lineage representing an assemblage of classes of unspecified scale. The "actual phase assemblage" spans a duration of time, whereas the "imagined phase assemblage" occupies a point in time, suggesting it was extensionally derived

they share, the stronger the hypothesis of "phyletic relationship" (Clarke 1968:211).

This really wasn't much different than Kroeber's (1931:151) distinction between similarities that are "specific and structural" and those that are "merely superficial." Clarke's real contribution to the issue, in Lyman's and my view, was how he illustrated his model of culture change, a version of which is shown in Fig. 14.1. Clarke's "type states" comprise assemblages of classes of some unspecified scale – attributes of discrete objects, types (attribute combinations) of discrete objects, or assemblages of particular types of discrete objects. An X combined with one or more primes designate each assemblage of material. In our terms, the primes designate a particular lineage; the bottom of the graph comprises lineage X′ and the two branches lineages X″ and X‴. The Arabic numbers denote the sequence of assemblages 1–4, within each of the two branches. Each "type state" comprises, then, a particular cultural unit within a lineage.

Lyman and I suspected that Clarke was signifying the ideational and extensional nature of cultural units with his "imagined phase assemblage" and was distinguishing them from the empirical reality of his "actual phase assemblage." We found this reasonable because he described variation in artifacts as multidimensional, or polythetic, and constantly changing, and Fig. 14.1 shows the "actual phase assemblage" encompassing a time period – the cylinder section is slanted – whereas the 'imagined phase assemblage' encompasses a single point in time – the cylinder section is horizontal. Clarke (1968:46) wrote that a cultural "system is dynamic and continuous, with the attributes or entities [artifact types] having specific values or states which vary by successive transformations". I return to character states and homologous change in a later section, where the discussion turns to replicators and transmission.

As Lycett and Chauhan (Chap. 1, this volume) point out, much of the current archaeological interest in issues of cultural transmission and the phylogenetic histories of cultural traditions owes an intellectual debt both to culture history and to Clarke's *Analytical Archaeology* (O'Brien and Lyman 2000; Shennan 2004), although Clarke's writings could be obtuse at times, and as a result, his take-home message was telegraphed as opposed to being fully explicated.[3] Thus archaeologists failed to appreciate the significant implications of Clarke's model, which rested on the related notions of cultural transmission and heritable continuity. Although he was not in any sense explicit about it, Clarke obviously viewed seriation as a means of testing for heritable continuity – a point my colleagues and I (O'Brien and Lyman 2000, 2003; O'Brien et al. 2001, 2002) have demonstrated empirically, especially with respect to occurrence seriation. If, as we will see later, one can reliably test for heritable continuity, then one can begin to distinguish between analogs and homologs.

Cultural Transmission

Cultural transmission is a primary determinant of behavior, and there is little doubt that it is one of the most effective means of evolutionary inheritance that nature could ever develop. Some (e.g., Gould 1996) argue that culture, through

its highly creative transmission processes, has exempted humans from natural selection, and thus from evolution, but a growing number of social scientists are rejecting this myopic view and instead are finding themselves in agreement with Bettinger and Eerkens's (1999:239) claim that "it seems clear to us that cultural transmission must affect Darwinian fitness – how could it be otherwise? And Darwinian fitness must also bear on cultural transmission. Again, how could that not be true? … To deny that would imply that the culturally mediated evolutionary success of anatomically modern humans is merely serendipitous happenstance."

Numerous studies conducted over the past three decades have modeled cultural-transmission processes and the strategies/biases that shape the results of transmission – conformist bias, prestige-based bias, indirect bias, drift, and the like (e.g., Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1981; Eerkens and Lipo 2005, 2007; Henrich 2001; Henrich and Boyd 1998; Henrich and Gil-White 2001). Recent empirical investigations, both in the field and in the laboratory (e.g., Bentley et al. 2004; Bettinger and Eerkens 1999; Eerkens 2000; Eerkens and Lipo 2008; Henrich 2004; Kohler et al. 2004; MacDonald 1998; McElreath et al. 2005; Mesoudi and Lycett 2009; Mesoudi and O'Brien 2008a, b; Shennan and Steele 1999; Shennan and Wilkinson 2001), not only reflect our growing ability to empirically test logical implications of such models but also underscore the variety and complexity of the transmission process (Shennan 2008a, b).

To me, this is one of the most exciting arenas of archaeology, and Paleolithic datasets from both the New World and the Old World have figured prominently in discussions. Bettinger and Eerkens (1999) were, I suspect, the first to apply formal cultural-transmission models to the archaeological record, using projectile points from the Great Basin. There, the bow and arrow replaced the atlatl around A.D. 300–600 – a replacement documented by a reduction in size of stone projectile points. The weight and length of points manufactured after A.D. 600, however, is not uniform across the region. Rosegate points from central Nevada vary little in weight and basal width, whereas specimens from eastern California exhibit significant variation in those two characters.

Bettinger and Eerkens proposed that the variation is attributable to differences in how the inhabitants of the two regions obtained and subsequently modified bow-related technology. In eastern California, bow-and-arrow technology was both maintained and perhaps spread initially through what Boyd and Richerson (1985) referred to as "guided variation," wherein individuals acquire new behaviors by copying existing behaviors and then modifying them through trial and error to suit their own needs. Conversely, in central Nevada bow-and-arrow technology was maintained and spread initially through "indirect bias," a form of learning wherein individuals acquire complex behaviors by opting for a single model on the basis of a particular trait identified as an index of the worth of the behavior. Bettinger and Eerkens proposed that in cases where cultural transmission is through guided variation, human behavior will tend to optimize fitness in accordance with the predictions of the genetic model – individual fitness is the

index of success, with little opportunity for the evolution of group-beneficial behaviors. In instances where transmission is through indirect bias, which tends to produce behaviorally homogeneous local populations, conditions may be right for the evolution and persistence of group-beneficial behaviors (Henrich and Boyd 1998; Richerson et al. 2003).

As Shennan and I noted (O'Brien and Shennan 2010), theoretical models are powerful tools, and applications of the models to actual data are why we do science, but controlled "middle-range" experiments provide the necessary bridge between the two (e.g., McElreath et al. 2005; Mesoudi 2008a, b, 2010). In that vein, Mesoudi and I (Mesoudi and O'Brien 2008a, b) designed an experiment to examine the cultural transmission of projectile-point technology, simulating the two transmission modes – indirect bias and guided variation – that Bettinger and Eerkens suggested were responsible for differences in Nevada and California point-attribute correlations. In brief, groups of participants designed "virtual projectile points" and tested them in "virtual hunting environments" with different phases of learning simulating indirectly biased cultural transmission and independent individual learning. As predicted, periods of cultural transmission were associated with significantly stronger attribute correlations than were periods of individual learning. This obviously has ramifications for how one looks at innovation. In simplified terms, more "loners," more innovation; more conformist individuals who want packages off the shelf, less innovation. The experiment and subsequent agent-based computer simulations showed that participants who engaged in indirectly biased horizontal cultural transmission outperformed individual-learning controls (individual experimentation), especially in larger groups, when individual learning is costly and the selective environment is multimodal (Mesoudi 2008b; Mesoudi and O'Brien 2008a, b). This was not unexpected, given Henrich's (2001) finding that biased cultural transmission is the predominant force in behavioral change.

Cultural transmission in a multimodal adaptive landscape, where point-design attributes are governed by bimodal fitness functions, yields multiple locally optimal designs of varying fitness (Mesoudi 2008b, 2009). Mesoudi and I hypothesized that innovations, represented by divergence in point designs resulting from individual experimentation (guided variation), were driven in part by this multimodal adaptive landscape, with different individuals converging by chance on different locally optimal peaks. We then argued that biased horizontal cultural transmission, where individuals copy the most successful person in their environment, allows individuals to escape from these local optima and to jump to the globally optimal peak (or at least the highest peak found by people in that group). Experimental results supported this argument, with participants in groups outperforming individual controls when the group participants were permitted to copy each other's point designs. This finding is potentially important to the production of innovation, as it demonstrates that the nature of the selective environment will significantly affect aspects of cultural transmission (Henrich and Boyd 1998; Mesoudi 2008b, 2010; Toelch et al. 2009).

Cultural Transmission and Lineages

Cultural transmission creates lineages, whether they be lineages of ideas, languages, manuscripts, recipes, or objects. Languages are perhaps the most straightforward cultural datasets for tracing historical patterns of descent (e.g., Gray and Atkinson 2003; Gray et al. 2009; Greenhill et al. 2009; Holden 2002; Rexová et al. 2003) because word retentions and replacements are fairly obvious. The more retentions two languages share, the more closely related they are. This, of course, presupposes that we can remove "loan words" from vocabulary lists. The notion that formal similarity can be used to indicate heritable continuity between cultural phenomena appears to have originated with the use of the comparative method in linguistic studies of the late eighteenth and early nineteenth centuries (Platnick and Cameron 1977). Similarities between the goals of systematic biology and those of historical linguistics have long been noted, dating back at least to the nineteenth century (Wells 1987). Darwin (1859:422) noted the similarity in the *Origin*: "If we possessed a perfect pedigree of mankind, a genealogical arrangement of the races of man would afford the best classification of the various languages now spoken throughout the world; and if all extinct languages, and all intermediate and slowly changing dialects, had to be included, such an arrangement would, I think, be the only possible one." Darwin was speaking of a language taxonomy that resembles the Linnaean taxonomy, but a truer representation is a phylogenetic (historical) tree, which shows ancestors and descendants as opposed to increasingly generalized groups of hierarchically ordered taxa whose historical relationships are obscured (O'Brien and Lyman 2003).

One method that is seeing increased use in formulating hypotheses of cultural descent is cladistics, a set of methods routinely used in biology and paleobiology to construct phylogenetic hypotheses (Collard and Shennan 2008). Like evolutionary taxonomy, cladistics uses only homologous characters to determine phylogeny, but it goes one step further and focuses strictly on "shared derived characters" – those held in common by two or more taxa and their immediate ancestor but no other taxon. In contrast, "shared ancestral characters" are homologous characters held in common by taxa that are related through more than a single ancestor. These are of less use because they do not allow us to order the taxa that have the characters. All we know is that the taxa are somehow related to each other. For example, the presence of a highly complex structure such as a vertebral column is evidence that humans, birds, and literally thousands of other taxa are somehow related. This relatedness is part of the reason for the identification of the subphylum Vertebrata. But the vertebral column is a character that extends so far back in time as to be essentially useless in terms of helping us understand how the myriad backboned organisms of the last 400 million years are related phylogenetically.

To say that cladistics focuses strictly on homologous characters in order to determine phylogeny, and then on only a single kind of homologous character, begs the question of how one sorts homologous characters from analogous characters – those that two or more taxa acquire independently as opposed to through relatedness. As pointed out earlier, this is at least as significant an issue in cultural

phylogeny as it is in biological phylogeny, and, like their colleagues who work in the strictly organic world, cultural phylogenists use a number of quantitative methods for identifying and separating homologs from analogs (O'Brien and Lyman 2003). Lycett (Chap. 9, this volume) reviews a number of these; suffice it to say here that these are highly preferable to attempting to identify "similarities [that] are specific and structural and not merely superficial" (Kroeber 1931:151).

Phylogenetic analysis has been used in archaeology to create histories of artifacts and assemblages (e.g., Collard and Shennan 2000; Jordan and Shennan 2003; Tehrani and Collard 2002), and stone tools have figured prominently in much of this work (e.g., Beck and Jones 2007; Buchanan and Collard 2007, 2008; Darwent and O'Brien 2006; Eerkens et al. 2006; Foley 1987; Lycett 2007, 2009; O'Brien and Lyman 2003; O'Brien et al. 2001, 2002). The logical basis for extending cladistics into archaeology is the same as it is in biology: Artifacts are complex systems, comprising any number of replicators, units analogous to genes (Hull 1988). The key word here is "analogous." Although I agree with Richerson et al. (2003:366) that "processes of cultural evolution can behave differently in critical respects from those only including genes," there is considerable merit in viewing artifacts not only as "simple extensions of hands, claws and teeth" (Kuhn 2004:561) but as comprising a hierarchy of replicators (Mesoudi and O'Brien 2008c; O'Brien et al. 2010).

As Hull (1981:32) put it, "a replicator must be small enough to retain its structural pattern through numerous replications, yet large enough to have a structural pattern worth preserving." Pocklington and Best (1997) argue that from an analytical standpoint, appropriate replicators will be the largest units that reliably and repeatedly withstand transmission. Why? There could be two reasons. First, the evolution of smaller units is likely controlled by the transmission of cultural traits defined at a higher level (Shennan 2004). Second, the parallel transmission of multiple smaller-scale units over long periods of time indicates that there is no significant conflict of interest among the subcomponents (Bull 1994). From an evolutionary perspective, parallel transmission is the force that initiates the process by which multiple isolated elements begin to cooperate with one another and create larger-scale structural integrity, which is the scale at which adaptations begin to form.

It is axiomatic in the social sciences that, with rare exceptions, technologies and practices are not reinvented anew each generation; rather, they are learned from other members of society (see papers in O'Brien and Shennan 2010a; Stark et al. 2008). Moreover, technologies are cumulative, which is a hallmark of human culture (Boyd and Richerson 1996). The kinds of changes that occur over generations of, say, stone-tool production are constrained, meaning that new structures and functions almost always arise through modification of existing structures and functions as opposed to arising de novo (Mesoudi and O'Brien 2008c). Ethnographic studies of modern nonindustrial peoples suggest that functionally interlinked, recipelike behavioral knowledge is acquired from others through a lengthy period of observation and instruction (Schiffer and Skibo 1987; VanPool et al. 2008). Given such a lengthy period of learning, recipelike behavior is most likely to be acquired from parents, with whom offspring spend most of the time and have more opportunity to observe (Mesoudi and O'Brien 2008c). This is consistent with anthropological evidence that cultural

transmission is predominantly vertical in many traditional societies for many traits (e.g., Guglielmino et al. 1995; Hewlett and Cavalli-Sforza 1986; Hewlett et al. 2002; O'Brien et al. 2008; Ohmagari and Berkes 1997), including specific ethnoarcheological evidence for the vertical transmission of material culture (Neff 1992; Shennan and Steele 1999; VanPool et al. 2008). The history of technological changes, which include additions, losses, and transformations, is recorded in the similarities and differences in the complex characteristics of related objects, that is, in objects that have common ancestors. This is what creates the tool "traditions" that are so familiar to archaeologists (Lyman et al. 1997).

Despite the growing number of social scientists who view cladistics as a useful analytical tool, there are outspoken critics of using any phylogenetic method to unravel culture history. So the argument goes, cultural phylogeny is impossible to reconstruct because of the nature of cultural evolution (e.g., Moore 1994; Terrell 2004). Critics view cultural evolution as a vastly different kind of process than biological evolution, with a faster tempo and often a different mode, often referred to as *reticulation.* They argue that the faster tempo and different mode act in concert to swamp most or all traces of phylogenetic history and thus reduce the cultural landscape to little more than a blur of interrelated forms. This line of reasoning is not new: Anthropologists from the late nineteenth century on have recognized that horizontal transmission produces reticulation (Lyman et al. 1997). But it needs to be pointed out that biological evolution can also involve reticulation (Arnold 1997; Jablonka and Lamb 2005), yet the presence of populations of hybrids, or *complex taxa* (Skála and Zrzavý 1994), has not precluded phylogenetic analysis. A key issue here is that critics of cultural phylogenetic analyses have used the term *hybridization* to denote *any* instance of horizontal transmission, and have therefore inappropriately conflated process (hybridization) with mode (reticulation) (O'Brien et al. 2008).

Still, no one ever said untangling phylogenetic histories was easy – a point that applies equally well to biological and cultural datasets. Cultural datasets can be downright messy if not vexing (e.g., Borgerhoff Mulder et al. 2006; Collard and Shennan 2000; Dewar 1995; Eerkens et al. 2006; Hosfield 2009; Nunn et al. 2006; Riede 2009; Terrell 1988), and critics raise valid questions with respect to being able to sort out vertical versus horizontal transmission. One question is whether horizontal transmission mutes a phylogenetic signal to the point where it is undetectable. The answer is "maybe," but it needs to be demonstrated on a case-by-case basis. It is worth pointing out, however, that several studies (e.g., Collard et al. 2006a, b) comparing cultural phylogenies to nonhuman biological phylogenies have found that cultural datasets appear to fit, on average, a tree model equally as well as biological datasets.

An even larger question is, at what scale are we examining transmission? At the scale of the individual? At the scale of the group? At an even larger, more inclusive scale? At the scale of the individual, any social learning that is done outside the parent–offspring will be "noisy" as far as a strict definition of "tradition" goes (VanPool et al. 2008). Oblique transmission, say, from teacher to student, will produce some noise, whereas horizontal transmission between peers will render the

signal undetectable. The issue is one of scale. Anthropologists rarely study individuals; their emphasis is on collections of individuals. At the level of the cultural group, purposely left undefined here, it probably doesn't matter who is teaching whom; there is still a phylogenetic signal, which for the sake of simplicity we can call a groupwide "tradition," and it will be distinct from those produced by other cultural groups. It is worth keeping in mind the comment by Borgerhoff Mulder et al. (2006) that when Cavalli-Sforza and Feldman (1981) first used the terms "horizontal" and "vertical" in reference to cultural transmission, they were referring to individuals, not groups. Even vertical transmission at the individual level can produce blending if individuals marry into new groups, just as horizontal transmission can produce branching if it is restricted within groups.

This caveat underscores what several of my colleagues and I (O'Brien et al. 2008) recently pointed out with respect to phylogenetic trees: Although they can be extremely useful for understanding large-scale patterns of cultural transmission, we view them as only one weapon in the anthropologist's toolkit. Other methods – simulation (Nunn et al. 2006), split-decomposition graphs (Bandelt and Dress 1992), tests for serial independence (Abouheif 1999), iterated parsimony (McElreath 1997), network analysis (Cochrane and Lipo 2010; Forster and Toth 2003; Jordan 2009; Lipo 2006), Bayesian methods such as Markov chain Monte Carlo (Huelsenbeck et al. 2000), component analysis (Riede 2009), tests for matrix correspondence (Smouse and Long 1992), assessment of hierarchical cluster structure (Pocklington 2006), and seriation (O'Brien and Lyman 2000) – should be used in tandem with cladistics. To quote Husan and Bryant (2006:254), "even when evolution proceeds in a tree-like manner, analysis of the data may not be best served by forcing the data onto a tree or tree-like mode. Rather, visualization and exploration of the data to discover and evaluate its properties can be an essential first step."

What Might Come Next?

Based on this admittedly brief and nonrandom foray through what I see as some of the interesting work that has been done with respect to cultural transmission and the American Paleolithic, what might it tell us about possible directions of future studies? I would suggest that one fruitful direction would be linking the pattern studies – phylogenetic histories, for example – with the macro- and micro-processes that create them. Here I am not talking so much about specific learning processes – guided variation, indirect bias, and so on – which, as we have seen, structure phylogenetic histories, as I am about evolutionary processes, or modes: *cladogenesis* – the splitting of a taxon into multiple taxa; *anagenesis* – the straight-line evolution of one taxon into another; and *hybridization* – the production of a new taxon as a result of interactions between or among multiple taxa. All three processes exist in both the biological world and the cultural world (O'Brien and Lyman 2000). I view cladogenesis and hybridization as macroevolutionary processes and anagenesis primarily as a microevolutionary process. This follows the way in which the distinction is usually made in biology,

Taxon	I	II	III	IV	V	VI	VII
A	1	6	6	1	4	3	6
B	1	4	6	4	4	3	6
C	1	4	6	4	4	2	6
D	1	4	5	4	4	2	4
E	1	4	5	3	4	2	4
F	1	3	5	3	3	2	4
G	1	3	5	5	3	1	4
H	1	3	4	5	3	1	4
I	1	3	4	5	2	1	3
J	1	2	4	5	2	4	3
K	1	2	4	2	2	4	3
L	1	2	1	2	5	4	3

Character

Fig. 14.2 Occurrence seriation of 12 taxa (A–L) showing the evolution of character states through time (from O'Brien et al. 2002). Each row is a particular character (I–VII); each Arabic numeral in a column denotes a particular character state. *Circled* character states denote a change from the state immediately below, as if time passed from *bottom* to *top*

where anagenesis is viewed as the production of intraspecific, small-scale changes that organisms go through as they pass from one generation to the next.

We can model microscale changes as in Fig. 14.2, which shows a hypothetical arrangement of twelve projectile-point classes (A–L) and seven character states (I–VII). The classes are in temporal order, with the earliest on the bottom and the latest on the top. In fact, in this example, the classes have been ordered chronologically by occurrence seriation, using the character-state changes [see O'Brien and Lyman (2003) for details]. Circled character states signify a change in state from the preceding class. For example, there are two changes in character state – one in character III (1→4) and another in character V (5→2) – from Class L at the bottom to the next class (K). Importantly, all 12 classes share either five or six character states with their immediate neighbor(s). Given the sequence as constructed, heritable continuity is evident because of considerable overlap in character states across adjacent classes.

Compare Fig. 14.2 with Clarke's model shown in Fig. 14.1. Although he did not use the term "heritable continuity," Clarke implied as much when he wrote that a cultural "system is dynamic and continuous, with the attributes or entities [artifact types] having specific values or states which vary by successive transformations"

(Clarke 1968:46). "Successive transformations" are nothing but replicators doing their work, effecting small change upon small change over varying amounts of time. Anagenesis is a perfectly acceptable term for this kind of change.

What about the tempo of the processes? Is the apparent rapid emergence of a new form – the Clovis point, for example – actually sudden or is it an illusion, meaning that the scale at which we are examining something makes it appear as if the object is new when in actuality it is the product of myriad small-scale cumulative modifications that took place over a relatively long period of time? Again, it becomes both a matter of scale and the amount of time that has elapsed between events of change (at various scales). Equally important, are process and tempo correlated, and if so, how? In paleobiology, the notion of *punctuated equilibrium* (Eldredge and Gould 1972; Gould and Eldredge 1977) was formulated to deal with that correlation, specifically the apparent sudden appearance of new forms. Eldredge and Gould argued that cladogenesis is the general mode under which evolution operates (as opposed to anagenesis) and that rapid cladogenesis is orders of magnitude more important than gradualism as a tempo of speciation. This, again, is a matter of scale and timing. At the scale of species recognition, which is what Gould and Eldredge are talking about, they undoubtedly are correct that rapid cladogenesis is much more important than gradualism. But underlying the eventual rapid splitting event are countless small, slow build-ups of change.

With cultural phenomena, those small build-ups are the result of individual episodes of cultural transmission. Finally, enough build-ups lead to literally a burst of variation, which Schiffer (1996) refers to as *stimulated variation*. Often, these bursts of variation are associated with underlying technological or social changes that make possible new approaches to mitigating perceived deficiencies in a particular design – a process Schiffer (2005) labels as the *cascade effect*. Changes in the context of cultural transmission, "often including the introduction of new cultural traits or shifts in previously unrelated or marginally related cultural traits, fundamentally alter artifact traditions and their selective environments. This creates new adaptive spaces in which artifact traditions change in response to new selective pressures" (Lyman et al. 2009:4).

As an example of how punctuated equilibrium might apply to an archaeological case, Lyman and I (O'Brien 2005, 2007; O'Brien and Lyman 2000) sketched out one possibility with respect to weapon-delivery systems in western North America after roughly 9250 B.C. At issue was the evolutionary placement of point types such as Clovis, Folsom, Meserve, and Goshen and the rapidity with which point types evolved. There is little doubt that point evolution was rapid and, at the scale of point type, cladogenetic. But at a finer level, there is no reason to dismiss anagenesis as a mechanism; after all, it is the small-scale changes – replacements as opposed to splittings – that over time eventually yield large-scale cladogenetic patterns. We know that some of these small-scale changes can result from selection – and that includes biased transmission – whereas others are the result of drift.

Determining whether a character or suite of characters is the product of selection or drift is not always straightforward. In an excellent study that built on Eerkens and Lipo's (2005) analysis of copying error (see also Eerkens and Lipo 2008),

Hamilton and Buchanan (2009) found that differences in the size of Clovis points through time and space across North America was the result of an accumulation of stochastic copying error, or drift. Similarly, Morrow and Morrow (1999) proposed that the monotonic increase in "fishtailness" of early fluted points from the Americas was the product not of adaptive convergence but of "stylistic drift … a process inherent in the ongoing translation of cultural practices from one generation to another under specific geographic and historical circumstances" (Morrow and Morrow 1999:227). In another paper, Buchanan and Hamilton (2009) tested Morrow and Morrow's proposition and found support for the drift hypothesis. Despite variation in regional North American environments during the late Pleistocene, apparently not enough time elapsed for local selective gradients to have led to significant changes in Early Paleoindian points.

The paper by Hamilton and Buchanan (2009), which is likely to become a pivotal paper in North American Paleolithic studies, goes a step further than simply testing for drift and links pattern and process in several clever ways. Hamilton and Buchanan posit that Clovis-point technology was a product of strong biased transmission, one product of which was statistically constant variance over time. Biased transmission is recognized as a dominant process of social learning among humans (Henrich 2001), and as Hamilton and Buchanan point out, it is understandable why biased learning strategies would have played a key role in Clovis technologies. Clovis projectile-point manufacture is a complex procedure and would have required a significant amount of investment both in terms of time and energy to learn effectively. Under these conditions, it is likely that there was a significant amount of variation among the level of skill exhibited by tool makers, such that recognized master craftsmen likely would have held considerable prestige. Additionally, in a fast-moving and fast-growing population subject to the widespread environmental changes of the North American late Pleistocene landscape (Hamilton and Buchanan 2007), conformist bias would have been a highly effective strategy for social learning because under circumstances where ecological conditions change is, say, on a generational scale, the mean trait value is often optimal, leading to frequency-dependent bias, or conformism (Henrich and Boyd 1998). However, if ecological conditions change faster, social learning may favor individual trial and error or even a combination of the two (Toelch et al. 2009).

Conclusion

Perhaps the take-home message in all this is found in the success that evolutionary biology enjoyed once the macroevolutionary patterns observed by paleontologists came to be seen as the long-term population-level result of the microevolutionary principles of genetic inheritance found by laboratory geneticists. Huxley (1942) famously labeled this the "Modern Synthesis." We will be led to a similar synthesis in Paleolithic archaeology if we view cultural macro- and micro-evolution within a

single overarching framework (Jordan 2009; Lyman and O'Brien 2001; Mesoudi and O'Brien 2009; Mesoudi et al. 2006; O'Brien and Lyman 2000). This means that we view the large-scale patterns observed in the archaeological record as the result not only of specific biases in cultural transmission at the microevolutionary level but also of evolutionary processes such as cladogenesis, anagenesis, and hybridization.

Here is one way to look at it (O'Brien and Lyman 2009): Let's say we are walking toward a large painting and starting to focus on smaller and smaller sections of it. At some distance from the canvas, we can see the entire painting and its overall design; such a macroview is indispensable, but by itself, it obscures details that become apparent only as we get closer and closer to the canvas. At close range we start to see the microstructure – individual brush marks, the layering of paint, and so forth – that undergirds the larger composite. In anthropological terms, those brush marks are the results of individual transmission events that together give rise to the large-scale patterns we see in the archaeological record. Are those microscale results evident in the archaeological record? No, but their proxies are – the billions upon billions of stone tools and the by-products of their manufacture and use that constitute the Paleolithic record.

To return to the point that I used to open this essay, from an evolutionary standpoint, the value of these proxies rests on our ability to sort out analogs from homologs. Some might argue that this is a straw man, that modern archaeology has refined the analytical means to deal with the issue. Maybe, but I'm not convinced that those means are used in all quarters. For an interesting example from the American Paleolithic, take a look at the debate over the reasons behind resemblances between Clovis tools from the United States and Solutrean tools from western Europe. Was there a Solutrean origin for Clovis culture, as Bradley and Stanford (2004) contend, or are the similarities a result of convergence, as Straus et al. (2005) maintain? There is no doubt in my mind – and that of the vast majority of North American archaeologists – that Bradley and Stanford are wrong, but the debate is of interest because it highlights several issues involved in distinguishing between analogs and homologs. With respect to the Clovis–Solutrean issue, there is a barrage of evidence against a homologous relation that overrides the fact that some similarities exist between Solutrean and Clovis stone tools. For example, Native Americans have five major haplogroups in mtDNA and two in the nonrecombining portion of the Y chromosome, which points out an Asian origin for Clovis, not a European one. Further, there are large chunks of Solutrean culture, including rock art, that are missing from Clovis sites. As Straus et al. (2005) point out, for the Solutrean origin of Clovis to make sense, there would had to have been a cultural as well as a genetic amnesia on the part of Solutrean colonists once they arrived on the North American continent.

How many archaeological examples have this kind of "barrage of evidence?" Not many. Most times, we are left with a meager record of tools and the by-products of their manufacture and use. How many times have homologous relations been posited on a whole lot less evidence than what has been brought to bear in the Solutrean–Clovis debate? The number is probably countless. In addition, the two proponents of the Solutrean-origin hypothesis, Bruce Bradley and Dennis Stanford, have seen more Clovis-age tools than most of us combined, and Bradley is an

expert flintknapper who knows Clovis stone-tool technology inside and out. If they can be wrong in assessing homologous relations, then that should give us some reason to pause. We might ask ourselves if it wouldn't be better to rely on some of the quantitative methods discussed here rather than on experience and intuition.

Notes

1 Binford (1972) was not quite as impressed with Clarke's book.
2 Recall Kroeber's (1948) depiction of the ever-branching tree of organic evolution versus the reticulate tree of cultural evolution.
3 For a readable account of some of what Clarke proposed, see Shennan (2004).

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References

Abbott, C.C., 1881. *Primitive Industry*. Bates, Salem, MA.
Abouheif, E., 1999. A method for testing the assumption of phylogenetic independence in comparative data. *Evolutionary Ecology Research* 1: 895–909.
Arnold, M.L., 1997. *Natural Hybridization and Evolution*. Oxford University Press, New York.
Bandelt, H.J. and Dress, A.W., 1992. Split decomposition: a new and useful approach to phylogenetic analysis of distance data. *Molecular Phylogenetics and Evolution* 1: 242–252.
Beck, C. and Jones, G.T., 2007. Early Paleoarchaic point morphology and chronology. In *Paleoindian or Paleoarchaic? Great Basin Human Ecology at the Pleistocene–Holocene Transition*, edited by K.E. Graf and D.N. Schmitt, pp. 23–41. University of Utah Press, Salt Lake City.
Bentley, R.A., Hahn, M.W. and Shennan, S.J., 2004. Random drift and culture change. *Proceedings of the Royal Society B* 271: 1443–1450.
Bettinger, R.L. and Eerkens J., 1999. Point typologies, cultural transmission, and the spread of bow-and-arrow technology in the prehistoric Great Basin. *American Antiquity* 64: 231–242.
Binford, L.R., 1968. Archeological perspectives. In *New Perspectives in Archeology,* edited by S.R. Binford and L.R. Binford, pp. 5–32. Aldine, New York.
Binford, L.R., 1972. Contemporary model building: paradigms and the current state of Paleolithic research. In *Models in Archaeology*, edited by D.L. Clarke, pp. 109–166. Methuen, London.
Binford, L.R., 1973. Interassemblage variability – the Mousterian and the "functional argument." In *The Explanation of Culture Change*, edited by C. Renfrew, pp. 227–254. Duckworth, London.
Borgerhoff Mulder, M., Nunn, C.L. and Towner M.C., 2006. Cultural macroevolution and the transmission of traits. *Evolutionary Anthropology* 15: 52–64.
Boyd, R. and Richerson P.J., 1985. *Culture and the Evolutionary Process*. University of Chicago Press, Chicago.
Boyd, R. and Richerson P.J., 1996. Why culture is common, but cultural evolution is rare. *Proceedings of the British Academy* 88: 77–93.
Bradley, B. and Stanford, D., 2004. The North Atlantic ice-edge corridor: a possible Palaeolithic route to the New World. *World Archaeology* 36: 459–478.

Buchanan, B. and Collard, M., 2007. Investigating the peopling of North America through cladistic analyses of Early Paleoindian projectile points. *Journal of Anthropological Archaeology* 26: 366–393.
Buchanan, B. and Collard, M., 2008. Phenetics, cladistics, and the search for the Alaskan ancestors of the Paleoindians: a reassessment of relationships among the Clovis, Nenana, and Denali archaeological complexes. *Journal of Archaeological Science* 35: 1683–1694.
Buchanan, B. and Hamilton, M.J., 2009. A formal test of the origin of variation in North American early Paleoindian projectile points. *American Antiquity* 74: 279–298.
Bull, J.J., 1994. Virulence. *Evolution* 48: 1423–1437.
Cavalli-Sforza, L.L. and Feldman, M.W., 1981. *Cultural Transmission and Evolution*. Princeton University Press, Princeton, NJ.
Clarke, D.L., 1968. *Analytical Archaeology*. Methuen, London.
Cochrane, E.E. and Lipo, C.P., 2010. Network and cladistic analyses of Lapita decoration do not support branching evolution or regional population structure during colonization of Western Remote Oceania. *Philosophical Transactions of the Royal Society B* (in press).
Collard, M. and Shennan, S.J., 2000. Processes of culture change in prehistory: a case-study from the European Neolithic. In *Archaeogenetics: DNA and the Population Prehistory of Europe*, edited by C. Renfrew and K. Boyle, pp. 89–97. McDonald Institute for Archaeological Research, Cambridge.
Collard, M. and Shennan S.J., 2008. Patterns, processes, and parsimony: studying cultural evolution with analytical techniques from evolutionary biology. In *Cultural Transmission and Material Culture: Breaking Down Boundaries*, edited by M.T. Stark, B.J. Bowser, and L. Horne, pp. 17–33. University of Arizona Press, Tucson.
Collard, M., Shennan, S.J. and Tehrani, J., 2006a. Branching versus blending in macroscale cultural evolution: a comparative study. In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory*, edited by C.P. Lipo, M.J. O'Brien, M. Collard, and S.J. Shennan, pp. 53–63. Aldine, New Brunswick, NJ.
Collard, M., Shennan, S.J. and Tehrani, J., 2006b. Branching, blending, and the evolution of cultural similarities and differences among human populations. *Evolution and Human Behavior* 27:169–184.
Darwent, J. and O'Brien, M.J., 2006. Using cladistics to reconstruct lineages of projectile points from northeastern Missouri. In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory*, edited by C.P. Lipo, M.J. O'Brien, M. Collard, and S.J. Shennan, pp. 185–208. Aldine, New Brunswick, NJ.
Darwin, C., 1859. *On the Origin of Species by Means of Natural Selection; or the Preservation of Favoured Races in the Struggle for Life*. Murray, London.
Dewar, R.E., 1995. Of nets and trees: untangling the reticulate and dendritic in Madagascar prehistory. *World Archaeology* 26: 301–318.
Eerkens, J.W., 2000. Practice makes within 5% of perfect: visual perception, motor skills, and memory in artifact variation. *Current Anthropology* 41:663–668.
Eerkens, J.W., Bettinger, R.L. and McElreath, R., 2006. Cultural transmission, phylogenetics, and the archaeological record. In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory,* edited by C.P. Lipo, M.J. O'Brien, M. Collard, and S.J. Shennan, pp. 169–183. Aldine, New Brunswick, NJ.
Eerkens, J.W. and Lipo, C.P., 2005. Cultural transmission, copying errors, and the generation of variation in material culture and the archaeological record. *Journal of Anthropological Archaeology* 24: 316–334.
Eerkens, J.W. and Lipo, C.P., 2007. Cultural transmission theory and the archaeological record: providing context to understanding variation and temporal changes in material culture. *Journal of Archaeological Research* 15: 239–274.
Eerkens, J.W. and Lipo, C.P., 2008. Cultural transmission of copying errors and the evolution of variation in Woodland pots. In *Cultural Transmission and Material Culture: Breaking Down Boundaries*, edited by M.T. Stark, B.J. Bowser, and L. Horne, pp. 63–81. University of Arizona Press, Tucson.

Eldredge, N. and Gould, S.J., 1972. Punctuated equilibria: an alternative to phyletic gradualism. In *Models in Paleobiology*, edited by T.J.M. Schopf, pp. 82–115. Freeman, Cooper, San Francisco.

Figgins, J.D., 1927. The antiquity of man in America. *Natural History* 27: 229–239.

Foley, R.A., 1987. Hominid species and stone tool assemblages: how are they related? *Antiquity* 61: 380–392.

Foley, R.A. and Lahr, M.M., 2003. On stony ground: lithic technology, human evolution, and the emergence of culture. *Evolutionary Anthropology* 12: 109–122.

Ford, J.A., 1952. Measurements of some prehistoric design developments in the southeastern States. *American Museum of Natural History, Anthropological Papers* 44: 313–384.

Forster, P. and Toth, A., 2003. Toward a phylogenetic chronology of ancient Gaulish, Celtic, and Indo-European. *Proceedings of the National Academy of Sciences of United States of America* 100: 9079–9084.

Gould, S.J., 1991. The disparity of the Burgess Shale arthropod fauna and the limits of cladistic analysis: why we must strive to quantify morphospace. *Paleobiology* 17: 411–423.

Gould, S.J., 1996. *Full House: The Spread of Excellence from Plato to Darwin.* Harmony, New York.

Gould, S.J. and Eldredge, N., 1977. Punctuated equilibria: the tempo and mode of evolution reconsidered. *Paleobiology* 3: 115–151.

Gray, R.D. and Atkinson, Q.D., 2003. Language-tree divergence times support the Anatolian theory of Indo-European origin. *Nature* 426: 435–439.

Gray, R.D., Drummond, A.J. and Greenhill, S.J., 2009. Language phylogenies reveal expansion pulses and pauses in Pacific settlement. *Science* 323: 479–483.

Greenhill, S.J., Currie, T.E. and Gray, R.D., 2009. Does horizontal transmission invalidate cultural phylogenies? *Proceedings of the Royal Society B* 276: 2299–2306.

Guglielmino, C.R., Viganotti, C., Hewlett, B. and Cavalli-Sforza, L.L., 1995. Cultural variation in Africa: role of mechanisms of transmission and adaptation. *Proceedings of the National Academy of Sciences of United States of America* 92: 7585–7589.

Hamilton, M.J. and Buchanan, B., 2007. Spatial gradients in Clovis-age radiocarbon dates across North America suggest rapid colonization from the north. *Proceedings of the National Academy of Sciences of United States of America* 104: 15629–15634.

Hamilton, M.J. and Buchanan, B., 2009. The accumulation of stochastic copying errors causes drift in culturally transmitted technologies: quantifying Clovis evolutionary dynamics. *Journal of Anthropological Archaeology* 28: 55–69.

Henrich, J., 2001. Cultural transmission and the diffusion of innovations: adoption dynamics indicate that biased cultural transmission is the predominate force in behavioral change. *American Anthropologist* 103: 992–1013.

Henrich, J., 2004. Demography and cultural evolution: why adaptive cultural processes produced maladaptive losses in Tasmania. *American Antiquity* 69: 197–221.

Henrich, J. and Boyd, R., 1998. The evolution of conformist transmission and the emergence of between-group differences. *Evolution and Human Behavior* 19: 215–241.

Henrich, J. and Gil-White, F.J., 2001. The evolution of prestige: freely conferred deference as a mechanism for enhancing the benefits of cultural transmission. *Evolution and Human Behavior* 22: 165–196.

Hewlett, B.S. and Cavalli-Sforza, L.L., 1986. Cultural transmission among the Aka Pygmies. *American Anthropologist* 88: 922–934.

Hewlett, B.S., Silvestri, A. de and Guglielmino, C.R., 2002. Semes and genes in Africa. *Current Anthropology* 43: 313–321.

Holden, C.J., 2002. Bantu language trees reflect the spread of farming across Sub-Saharan Africa: a maximum-parsimony analysis. *Proceedings of the Royal Society B* 269: 793–799.

Holmes, W.H., 1893. A question of evidence. *Science* 21: 135–136.

Holmes, W.H., 1897. Stone implements of the Potomac–Chesapeake Tidewater Province. *Bureau of American Ethnology, Annual Report* 15: 13–152.

Hosfield, R., 2009. Modes of transmission and material culture patterns in craft skills. In *Pattern and Process in Cultural Evolution,* edited by S.J. Shennan, pp. 45–60. University of California Press, Berkeley.

Huelsenbeck, J.P., Rannala, B. and Masly, J.P., 2000. Accommodating phylogenetic uncertainty in evolutionary studies. *Science* 288: 2349–2350.

Hull, D. 1981. Units of evolution: a metaphysical essay. In *The Philosophy of Evolution*, edited by U.J. Jenson and R. Harré, pp. 23–44. St. Martin's Press, New York.

Hull, D., 1988. Interactors versus vehicles. In *The Role of Behavior in Evolution*, edited by H.C. Plotkin, pp. 19–50. MIT Press, Cambridge, MA.

Husan, D.H. and Bryant, D., 2006. Application of phylogenetic networks in evolutionary studies. *Molecular Biology and Evolution* 23: 254–267.

Huxley, J.S., 1942. *Evolution, the Modern Synthesis*. Allen and Unwin, London.

Jablonka, E. and Lamb, M.J., 2005. *Evolution in Four Dimensions: Genetic, Epigenetic, Behavioural, and Symbolic Variation in the History of Life*. Bradford, Cambridge, MA.

Jordan, P., 2009. Linking pattern to process in cultural evolution: investigating material culture diversity among the Northern Khanty of northwest Siberia. In *Pattern and Process in Cultural Evolution,* edited by S.J. Shennan, pp. 61–83. University of California Press, Berkeley.

Jordan, P. and Shennan, S.J., 2003. Cultural transmission, language and basketry traditions amongst the California Indians. *Journal of Anthropological Archaeology* 22: 42–74.

Kohler, T.A., VanBuskirk, S. and Ruscavage-Barz, S., 2004. Vessels and villages: evidence for conformist transmission in early village aggregations on the Pajarito Plateau, New Mexico. *Journal of Anthropological Archaeology* 23: 100–118.

Kroeber, A.L., 1931. Historical reconstruction of culture growths and organic evolution. *American Anthropologist* 33: 149–156.

Kroeber, A.L., 1948. *Anthropology* (rev. ed.). Harcourt Brace, New York.

Kuhn, S.L., 2004. Evolutionary perspectives on technology and technological change. *World Archaeology* 36: 561–570.

Lipo, C.P., 2006. The resolution of cultural phylogenies using graphs. In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory,* edited by C.P. Lipo, M.J. O'Brien, M. Collard, and S.J. Shennan, pp. 89–108. Aldine, New Brunswick, NJ.

Lubbock, J., 1865. *Pre-historic Times, as Illustrated by Ancient Remains, and the Manners and Customs of Modern Savages*. Williams and Norgate, London.

Lycett, S.J., 2007. Why is there a lack of Mode 3 Levallois technologies in East Asia? A phylogenetic test of the Movius-Schick hypothesis. *Journal of Anthropological Archaeology* 26: 541–575.

Lycett, S.J., 2009. Are Victoria West cores 'proto-Levallois'? A phylogenetic assessment. *Journal of Human Evolution* 56: 175–191.

Lyman, R.L., 2008. Cultural transmission in North American anthropology and archaeology, ca. 1895–1965. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M.J. O'Brien, pp. 10–20. Society for American Archaeology Press, Washington, DC.

Lyman, R.L. and O'Brien, M.J., 2001. Misconceptions of evolutionary archaeology: confusing macroevolution and microevolution. *Current Anthropology* 42: 408–409.

Lyman, R.L., O'Brien, M.J. and Dunnell, R.C., 1997. *The Rise and Fall of Culture History*. Plenum, New York.

Lyman, R.L., VanPool, T.L. and O'Brien, M.J., 2009. The diversity of North American projectile-point types, before and after the bow and arrow. *Journal of Anthropological Archaeology* 28: 1–13.

MacDonald, D., 1998. Subsistence, sex, and cultural transmission in Folsom culture. *Journal of Anthropological Archaeology* 17: 217–239.

McElreath, R., 1997. *Iterated Parsimony: A Method for Reconstructing Cultural Histories*. M.A. thesis, Department of Anthropology, University of California, Los Angeles. Los Angeles.

McElreath, R., Lubell, M., Richerson, P.J., Waring, T.M., Baum,W., Edsten, E., Efferson, C. and Paciotti, B., 2005. Applying evolutionary models to the laboratory study of social learning. *Evolution and Human Behavior* 26: 483–508.

Mesoudi, A., 2008a. The experimental study of cultural transmission and its potential for explaining archaeological data. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M.J. O'Brien, pp. 91–101. Society for American Archaeology Press, Washington, DC.

Mesoudi, A., 2008b. An experimental simulation of the "copy-successful-individuals" cultural learning strategy: adaptive landscapes, producer–scrounger dynamics, and informational access costs. *Evolution and Human Behavior* 29: 350–363.

Mesoudi, A., 2010. The experimental study of cultural innovation. In *Innovation in Cultural Systems: Contributions from Evolutionary Archaeology*, edited by M.J. O'Brien and S.J. Shennan, pp. 175–191. MIT Press, Cambridge, MA.

Mesoudi, A. and Lycett, S.J., 2009. Random copying, frequency-dependent copying and culture change. *Evolution and Human Behavior* 30: 41–48.

Mesoudi, A. and O'Brien, M.J., 2008a. The cultural transmission of Great Basin projectile-point technology I: an experimental simulation. *American Antiquity* 73: 3–28.

Mesoudi, A. and O'Brien, M.J., 2008b. The cultural transmission of Great Basin projectile-point technology II: an agent-based computer simulation. *American Antiquity* 73: 627–644.

Mesoudi, A. and O'Brien, M.J., 2008c. The learning and transmission of hierarchical cultural recipes. *Biological Theory* 3: 63–72.

Mesoudi, A. and O'Brien, M.J., 2009. Placing archaeology within a unified science of cultural evolution. In *Pattern and Process in Cultural Evolution,* edited by S.J. Shennan, pp. 21–32. University of California Press, Berkeley.

Mesoudi, A., Whiten, A. and Laland, K.N., 2006. Towards a unified science of cultural evolution. *Behavioral and Brain Sciences* 29: 329–383.

Moore, J.H., 1994. Putting anthropology back together again: the ethnogenetic critique of cladistic theory. *American Anthropologist* 96: 925–948.

Morrow, J.E. and Morrow, T.A., 1999. Geographic variation in fluted projectile points: a hemispheric perspective. *American Antiquity* 64: 215–230.

Neff, H., 1992. Ceramics and evolution. *Archaeological Method and Theory* 4: 141–193.

Nunn, C.L., Borgerhoff Mulder, M. and Langley, S., 2006. Comparative methods for studying cultural trait evolution: a simulation study. *Cross-Cultural Research* 40: 177–209.

O'Brien, M.J., 2005. Evolutionism and North America's archaeological record. *World Archaeology* 37: 26–45.

O'Brien, M.J., 2007. What's new? Some basic issues in anthropological studies of innovation. *Review of Archaeology* 28: 39–54.

O'Brien, M.J., Darwent, J. and Lyman, R.L., 2001. Cladistics is useful for reconstructing archaeological phylogenies: Palaeoindian points from the southeastern United States. *Journal of Archaeological Science* 28: 1115–1136.

O'Brien, M.J. and Lyman, R.L., 2000. *Applying Evolutionary Archaeology: A Systematic Approach*. Kluwer Academic/Plenum, New York.

O'Brien, M.J. and Lyman, R.L., 2003. *Cladistics and Archaeology*. University of Utah Press, Salt Lake City.

O'Brien, M.J. and Lyman, R.L., 2009. Darwinism and historical archaeology. In *International Handbook of Historical Archaeology*, edited by T. Majewski and D. Gaimster, pp. 227–252. Springer, New York.

O'Brien, M.J., Lyman, R.L., Collard, M., Holden, C.J., Gray, R.D., and Shennan, S.J., 2008. Phylogenetics and the evolution of cultural diversity. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M.J. O'Brien, pp.39–58. Society for American Archaeology Press, Washington, DC.

O'Brien, M.J., Lyman, R.L., Mesoudi, A., and VanPool, T.L., 2010. Cultural traits as units of analysis. *Philosophical Transactions of the Royal Society B* (in press).

O'Brien, M.J., Lyman, R.L., Saab, Y., Saab, E., Darwent, J., and Glover, D.S., 2002. Two issues in archaeological phylogenetics: taxon construction and outgroup selection. *Journal of Theoretical Biology* 215: 133–150.

O'Brien, M.J. and Shennan, S.J., (eds.) 2010a. *Innovation in Cultural Systems: Contributions from Evolutionary Anthropology*. MIT Press, Cambridge, MA.

O'Brien, M.J. and Shennan, S.J., 2010b. Issues in anthropological studies of innovation. In *Innovation in Cultural Systems: Contributions from Evolutionary Anthropology*, edited by M.J. O'Brien and S.J. Shennan, pp.3–17. MIT Press, Cambridge, MA.

Ohmagari, K. and Berkes, F., 1997. Transmission of indigenous knowledge and bush skills among the Western James Bay Cree women of subarctic Canada. *Human Ecology* 25: 197–222.

Platnick, N.I. and Cameron, D., 1977. Cladistic methods in textual, linguistic, and phylogenetic analysis. *Systematic Zoology* 26: 380–385.

Pocklington, R., 2006. What is a culturally transmitted unit, and how do we find one? In *Mapping Our Ancestors: Phylogenetic Approaches in Anthropology and Prehistory*, edited by C.P. Lipo, M.J. O'Brien, M. Collard, and S.J. Shennan, pp.19–31. Aldine, New Brunswick, NJ.

Pocklington, R. and Best, M.L., 1997. Cultural evolution and units of selection in replicating text. *Journal of Theoretical Biology* 188: 79–87.

Rexová, K., Frynta, D. and Zrzavý, J., 2003. Cladistic analysis of languages: Indo-European classification based on lexicostatistical data. *Cladistics* 19: 120–127.

Richerson, P.J., Boyd, R.T. and Henrich, J., 2003. Cultural evolution of human cooperation. In *Genetic and Cultural Evolution of Cooperation,* edited by P. Hammerstein, pp. 357–388. MIT Press, Cambridge, MA.

Riede, F., 2009. Tangled trees: modeling material culture evolution as host–associate cospeciation. In *Pattern and Process in Cultural Evolution,* edited by S.J. Shennan, pp. 85–98. University of California Press, Berkeley.

Schiffer, M.B., 1996. Some relationships between behavioral and evolutionary archaeologies. *American Antiquity* 61: 643–662.

Schiffer, M.B., 2005. The devil is in the details: the cascade model of invention processes. *American Antiquity* 70: 485–502.

Schiffer, M.B. and Skibo, J.M., 1987. Theory and experiment in the study of technological change. *Current Anthropology* 28: 595–622.

Shennan, S., 2000. Population, culture history, and the dynamics of culture change. *Current Anthropology* 41: 811–835.

Shennan, S., 2004. Analytical archaeology. In *A Companion to Archaeology*, edited by J. Bintliff, pp.3–20. Blackwell, Oxford.

Shennan, S.J., 2008a. Canoes and cultural evolution. *Proceedings of the National Academy of Sciences of United States of America* 105: 3175–3176.

Shennan, S.J., 2008b. Evolution in archaeology. *Annual Review of Anthropology* 37: 75–91.

Shennan, S.J. and Steele, J., 1999. Cultural learning in hominids: a behavioural ecological approach. In *Mammalian Social Learning: Comparative and Ecological Perspectives*, edited by H.O. Box and K.R. Gibson, pp. 367–388. Cambridge University Press, Cambridge.

Shennan, S.J. and Wilkinson, J.R., 2001. Ceramic style change and neutral evolution: a case study from Neolithic Europe. *American Antiquity* 66: 577–594.

Simpson, G.G., 1961. *Principles of Animal Taxonomy*. Columbia University Press, New York.

Skála, Z. and Zrzavý, J., 1994. Phylogenetic reticulations and cladistics: discussion of methodological concepts. *Cladistics* 10: 305–313.

Smouse, P.E. and Long, J.C., 1992. Matrix correlation analysis in anthropology and genetics. *Yearbook of Physical Anthropology* 35: 187–213.

Stark, M.T., Bowser, B.J. and Horne, L., (eds.), 2008. *Cultural Transmission and Material Culture: Breaking Down Boundaries*. University of Arizona Press, Tucson.

Straus, L.G., Meltzer, D.J., and Goebel, T., 2005. Ice age Atlantis? Exploring the Solutrean–Clovis 'connection.' *World Archaeology* 37: 507–532.

Tehrani, J. and Collard, M., 2002. Investigating cultural evolution through biological phylogenetic analyses of Turkmen textiles. *Journal of Anthropological Archaeology* 21: 443–463.

Terrell, J.E., 1988. History as a family tree, history as an entangled bank: constructing images and interpretations of prehistory in the South Pacific. *Antiquity* 62: 642–657.

Terrell, J.E., 2004. Review of "Cladistics and Archaeology" by M.J. O'Brien and R.L. Lyman. *Journal of Anthropological Research* 60: 303–305.

Toelch, U., van Delft, M.J., Bruce, M.J., Donders, R., Meeus, M.T.H., and Reader, S.M., 2009. Decreased environmental variability induces a bias for social information use in humans. *Evolution and Human Behavior* 30: 32–40.

VanPool, T.L., Palmer, C.T., and VanPool, C.S., 2008. Horned serpents, tradition, and the tapestry of culture. In *Cultural Transmission and Archaeology: Issues and Case Studies*, edited by M.J. O'Brien, pp.77–90. Society for American Archaeology, Washington, DC.

Wells, R.S., 1987. The life and growth of language: metaphors in biology and linguistics. In *Biological Metaphor and Cladistic Classification*, edited by H.M. Hoenigswald and L.F. Wiener, pp. 39–80. University of Pennsylvania Press, Philadelphia.

Willey, G.R., 1953. Archaeological theories and interpretation: New World. In *Anthropology Today*, edited by A.L. Kroeber, pp. 361–385. University of Chicago Press, Chicago.

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